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TITRE

A CONCEPTUAL MODEL FOR MULTIPOINTS OF VIEW ANALYSIS OF COMPLEX SYSTEMS. APPLICATION TO THE ANALYSIS OF THE CARBON DYNAMICS OF VILLAGE TERRITORIES OF THE WEST AFRICAN SAVANNA

SOUS-TITRE

UN MODÈLE CONCEPTUEL POUR LA REPRÉSENTATION ET L'ANALYSE MULTI-POINTS DE VUES DES SYSTÈMES COMPLEXES. APPLICATION À L'ANALYSE DE LA DYNAMIQUE DES RESSOURCES EN CARBONE DES TERROIRS VILLAGEOIS DE LA SAVANE OUEST-AFRICAINE

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Abstract

Modelling complex systems that cover multiple domains, for their better understanding, increasingly demands collaboration between different disciplines. However, these disciplines do not necessarily share the same points of view on the real objects of the system, and these can be complementary. In addition, the representation of such systems requires multi-scale description implying at least the local (individual), global and underlying environment. This PhD work proposes (1) a conceptual framework for complex systems analysis and representation from different points of view at the global and the local levels while taking into account the environment and (2) its application to the representation and analysis of the carbon dynamics from plot to village levels in the West African savannas (WAS).

Using multi-agent system (MAS) organizations-centered approach, the Organization-Role-Entity-Aspect (OREA) meta-model has been proposed to represent a complex system from different points of view. At the global level a point of view is reified as an organization made of the roles the entities can play in the organization; at the local level the points of view decompose an entity internal structure in a set of aspects. Through the concept of role, an entity can play different roles in different organizations. Through the concept of aspects, an entity can play a role in different ways. OREA is an extension of the Agent-Group-Role meta-model where: (1) roles are not limited to agents but can be assigned to any kind of object (including the environment), (2) the decomposition does not only apply to the organizations only, but also to the entities themselves, (3) the use of the framework for knowledge representation rather than a pure software engineering paradigm is emphasized.

OREA provides a framework to specify explicitly and separately the macro and the micro levels. The macro-level in OREA is specified without any assumption on the micro-level. The macro-level is relevant to the "what" while the micro-level is concerned by the "how". The environmental objects are explicitly defined in the organization structure allowing defining the perception of the environment by the entities through their roles. The OREA methodology allows specification of the structure of a system based on the identification of the scales of description and their underlying processes.

The OREA model has then been used for the modelling of the carbon (C) dynamics from plot to village levels in the WAS. Carbon is an important determinant of the sustainability of West African farming systems and of the greenhouse effect. To deal with the complexity of C dynamics various models have been developed to simulate and predict carbon dynamics. These models are mathematical, process-based or individual-based. To better include social and economic dimension and handle system heterogeneity a generic multi-agent model for the analysis of C dynamics at the village level, CaTMAS (Carbon Territory Multi-Agent Simulator), has been designed and implemented. CaTMAS assumes that a better analysis of C dynamics at the village level requires consideration of (1) social, economic, physical and biological factors, (2) the individual's actions and the multiplicity of interleaved dynamics. CaTMAS is based on the OREA model, the MAS approach, and coupling with the Century model and a Geographic Information System. The model allows a multiple-point-of-view analysis of C dynamics as organisations made of roles played by entities through various aspects. CaTMAS not only provides a framework for an explicit and realistic description of a farming system but also allows assessment of the viability of farming systems under various socio-economic and bio-physical scenarios. The model integrates the interactions between the human's activities and the environment and some environmental feedbacks. Using CaTMAS, it is possible to analyze how population growth impacts C dynamics and vice-versa. The model has been used to analyze the impacts of climate and economic change on the one hand, and of two cropping systems on the other hand, on the C dynamics of the village territory.

Future efforts on the OREA model should focus on improving the methodology and the verification and on taking into account the holonic representation. Developments on CaTMAS could include enlargement of simulations to the country scale and integration of the economic potential of the C market at the national, regional and the local levels.

Keywords: Complex system, Computer Simulation,Multi-Agents System, Multi-point of view, Organisation, OREA,Renewable resources, carbon resources, CaTMAS

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1.1 Towards a multi point of view representation of complex systems

Modelling complex systems (CS) that cover multiple domains, for their better understanding, increasingly demands collaboration between different disciplines. Müller (2004) defines a complex system (1) as a set of entities with non-linear behaviour, interacting with each other and evolving at least three scales of time and space and (2) such that the behaviour at the global scale cannot be reduced to the composition of the local behaviours. The analysis of such systems requires multi-scale description implying at least the individual, global and underlying environment (Müller, 2004). In addition, CS modelling requires consideration of several factors. These factors can concern one or several disciplines. For example, the carbon (C) dynamics at large scale encompasses the socio-economic and bio-physical dimensions. Then, the analysis of CS should include a variety of points of view from different disciplines. The different disciplines have not necessarily the same points of view on the objects of the system. However these points of view may be complementary and require to be taken into account to deal efficiently with the system complexity. Then, considering the properties of a CS, a multi point of view description requires to take into account the multiplicity of point of views at individual, global and environmental level. These different points of view must be explicitly defined for a better understanding of the system.

We distinguish several modelling approaches to CS: mathematical modelling (Hazell and Norton, 1986), automate cellular (Balman, 1997), individual-based modelling and multi-agent system (MAS). MAS treat a system as a set of agents interacting and evolving in an environment that they can perceive and modify through their actions. MAS provide a sustainable framework to handle simultaneously the individual and the global levels of a complex system, as well as the interaction with the environment. The ability of MAS to integrate heterogeneous agents in a same model, the autonomy of agents, their ability to make decisions about the interactions and the structure of the system at run-time make MAS more relevant than other modelling approaches to develop complex systems (Jennings, 2000, Wooldridge, 1997) as long as we are concerned with representing the CS at several levels at once (Ratzé et al., 2007).

Two approaches are currently used for building complex systems with MAS: the Agent-Centered Multi-Agent System (ACMAS) (Drogoul et al., 1995) and the Organisation-Centered Multi-Agent System (OCMAS) (Ferber and Gutknecht, 1998, Hübner et al., 2002).

1.1.1 The ACMAS models

The ACMAS approach is based on the agent-oriented point of view.

> *"In that view, the designer of a multi-agent system is only concerned with agents' individual actions, and it is supposed that social structures come from patterns of actions that arise as a result of interactions"* (Ferber and Gutknecht, 1998).

The structure of agent-centered models considers agents as the first class entity where each agent is defined by its internal state and set of operations defining its behaviour. Jennings and Wooldridge (2000) underline the limitations of ACMAS to deal efficiently with system complexity:

> *"Another common misconception is that agent-based systems require no real structure. While this may be true in certain cases, most agent systems require considerably more system-level engineering than this. Some way of structuring the society is typically needed to reduce the system's complexity, to increase the system's efficiency, and to more accurately model the problem being tackled."*

1.1.2 The OCMAS models

OCMAS models assume that the social structure must exist *a priori* and constrains the agents behaviour (Hübner et al., 2002). Unlike ACMAS models, OCMAS models treat MAS as organizations interacting through agents playing roles. OCMAS introduces the notion of organisation, role and agent to represent a system structure. An organisation defines a collection of roles and their relationship. A role defines in part the place of an agent in a system; it is closed to an organisation and can be played by several agents. Using organisation, it is possible to describe explicitly the organizational relationship and reduce the system complexity. It can be used to limit the scope of interactions, provide strength in number and reduce or manage uncertain (Horling and Lesser, 2005). The OCMAS models allow dealing efficiently with the heterogeneity of language, multiple applications and architectures, the security control and the modularity in MAS building (Horling and Lesser, 2005).

Several OCMAS models have been proposed. They can be classified according to the problem they aim to resolve and to their structure. Depending on their objectives, tree categories of models intending (1) to the decomposition of a system into sub-systems (Wooldrigde et al., 2000, Ricordel, 2001), (2) to the coordination and the collective tasks execution (Barbuceanu et al., 1998a, Hannoun et al., 2000) and (3) to the design of opened system (Esteva et al., 2001, Vazquez-Salceda et al., 2003) can be distinguished. Depending on their structure, one can identify tree categories of models: (1) role-based models intending to propose a social level and to take into account heterogeneity and modularity in the MAS (Ferber and Gutknecht, 1998, Wooldrigde et al., 2000, Hannoun et al., 1999), (2) component-based models very closed to software engineering intending to increase the reuse and modularity in MAS specification and (3) the models coupling the two first approaches (Amiguet et al., 2003).

However, most OCMAS models do not deal fulfill with the separation of concerns in CS modelling. They do not provide an explicit separation between "what" and "how". The macro and micro levels are not explicitly separated in these models limiting the genericity and the reuse of the organisational structure. The organisation behaviour is not separated from the behaviour of agents. In these models, the roles define both the status within organisation and behaviour of agents. Another limitation concern the environment specification. Most of these models do not consider the environment objects in organisation structure or not take into account the perception of the agents on their environment depending on their roles.

1.2 Objectives

The objectives of this study are :

1. to propose a conceptual framework allowing multi points of view description of complex systems at any level. This framework intends to be a language of the knowledge representation for the modelling of complex systems and simulation. This conceptual framework must allow a multi point of view analysis and description of a complex system both at individual and global levels while taking into account the integration of environment.

2. to build a methodology and language to help the designer in different processes of CS modelling.

3. the validation of the proposed framework toward a proposition of a generic model to simulate and analyse the C dynamics from plot to village level in West-Africa Savanna.

1.3 Contributions

Using the OCMAS approach, the Organisation-Role-Entity-Aspect (OREA) model has been proposed. OREA allows the representation of a complex system from different points of view: at the global level a point of view is reified as an organisation made from the roles the entities can play in the organisation, at the local level the points of view decompose an entity in a set of aspects. Through the concept of role, an entity can play different roles in different organizations. Through the concept of aspects, an entity can play a role in different ways. Using the notion of role and aspect, it is possible to separate the organisation behaviour and the entities behaviour from the internal point of view.

OREA is an extension of AGR (Ferber and Gutknecht, 1998) where: (1) the roles are not limited to agents but to any kind of objects (including the environment), (2) the decomposition does not apply only to the organizations, but also to the entities themselves, (3) the use of the framework for knowledge representation and modelling rather than a pure software engineering paradigm is emphasized. The OREA model has been implemented in the MIMOSA platform and provides two levels of description: the abstract level and the concrete level.

The OREA model has been tested and validated through the analysis, the design and the implementation of a simulation tool: the Carbon Territory Multi-Agents Simulation (CaTMAS) model. The CaTMAS is an integrated model allowing simulating the C dynamics from plot to territory levels while taking into account the socio-economic and bio-physical dimensions in West-African Savanna. The CaTMAS model takes into account the heterogeneity of farming system and the impact of human's activities on carbon dynamics, providing a perfect test case for OREA. The model has been coupled to the Century model and a geographical information system (GIS).

1.4 Thesis organisation

This thesis is organized as following:

Chapter 2: The complex system modelling and simulation describes the CS properties and discusses how computer simulation allows to deal with the CS understanding. In this chapter, we present computer modelling and simulation as (1) a tool for CS understanding,(2) a way to experiment in a virtual world the explanatory power of some hypotheses and (3) a tool for prediction and anticipation. In addition, we describe different types of computer simulation formalisms and underline their advantages and limitations.

Chapter 3: The Multi-Agent Systems are the background of our study. This chapter presents the MAS as a natural and relevant way to deal with the complexity. This chapter defines the concepts of MAS and the issues of MAS building . In addition, we provide a state of art of the OCMAS models and underline their advantages and limitations. Through this state of art, we present how the existing OCMAS models fail to deal with (1) the explicit separation between the organizational level and the agent level, (2) the integration of the environment in organisation structure and (3) the genericity of the organisation structure. This chapter allows to introduce the contribution of this thesis in CS modelling and simulation.

Chapter 4: The OREA model describes the main contribution of this document: the OREA model. From the structural point of view, the OREA model provides an explicit separation between the macro-level and the micro-level. In the OREA model, the macro-level is defined without doing assumptions on the micro-level. The objective is to provide a clear separation between the "what" defined by the macro-level and the "how" defined by the micro-level. The macro-level is generic and allows playing differently a same role type. To allow the entities to play a same role differently, we use the concept of aspect which implements a part of the entity behaviour. From the dynamics point of view, the OREA model allows an explicit description of a system dynamics from the external and the internal point of view.

Chapter 5: The conceptual framework of the CaTMAS model presents the CaTMAS model. CaTMAS is a multi-agents model assessing the carbon dynamics from plot to village level. This chapter aims at applying the OREA model to modelling of the carbon dynamics . A conceptual model is proposed using the OREA model. This conceptual framework provides an explicit and realistic description of the carbon dynamics at different scales of description while taking into account the social, economic and biophysical factors. It includes the land tenure, the crop and animal production, the carbon transport and transformation.

Chapter 6: Implementation and simulation describes the implementation of the CaTMAS model. The model has been implemented with MIMOSA model with a coupling with Century model and GIS. Some simulations have been done and analysed under various socio-economic and bio-physical scenarios. The results show the relationships between population of C resources and the climate impacts on the C sequestration.

Chapter 2

Complex system modelling and simulation

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En cet empire, l'art de la cartographie fut poussé à une telle perfection que la carte d'une seule province occupait toute une ville et la carte de l'Empire toute une province. Avec le temps, ces cartes démesurées cessèrent de donner satisfaction et les collèges de cartographes levèrent une carte de l'Empire, qui avait le format de l'Empire et qui coïncidait avec lui, point par point. Moins passionnés pour l'étude de la cartographie, les générations suivantes réfléchirent que cette carte dilatée était inutile et, non sans impiété, elles l'abandonnèrent à l'inclémence du soleil et des hivers.

Suarez MIRANDA, Viajes de Varones Prudentes (1658), imaginé par J.-L. Borges, Histoire universelle de l'infamie/Histoire de l'éternité, Union générale d'éditions, collection 10/18, Paris

2.1 Complex Systems Modelling

2.1.1 Definition of complex systems

There are many definitions of complex systems. Simon (1996) defines a CS as:

> *"A system that can be analyzed into many components having relatively many relations among them, so that the behaviour of each component depends on the behaviors of others."*

The components in a CS are not isolated. They are in relation and interact together them. They interact in unpredictable way so that it is impossible to define a priori the behaviour of the whole. From their interactions some global properties can emerge and constrain the components' behaviour:

> *"the interactions among the components are non-linear, such that the global behaviour of the system cannot be compositionally deduced from the components' behaviours"* (Müller, 2004).

Forrest (1990) sumurises the properties of CS as follow:

1. The system consists of a large number of interacting agents operating with the environment. Agents act on and are influenced by their local environment.
2. There is no global control over the system. All agents are only able to influence other agents locally.
3. Each agent is driven by simple mechanisms, typically condition-action rules, where the conditions are sensitive to the local environment. Usually, all agents share the same set of rules, although because they may be in different local environments, the actions they take will differ.

This description underlines the role of environment in a CS and the autonomy of the components. The environment drives interactions between components and constraints their behaviour. The components are autonomous: they control their own behaviour, but they are externally influenced by other components.

A farming system is an example of CS. It is characterized by several entities (e.g. farmer, animals) interacting at several spatio-temporal scales. The farmers interact among them e.g.

to exchange information, to coordinate their activities, to exchange good and labour power. Their decision-making process depends on their objectives and the environmental constraints (e.g. spatial location, rainfall, soil fertility). In addition, farmer's decision-making is influenced by the strategies of other farmers. For example, to use a common resource such as water, each farmer must take into account the strategies of other farmers to make decisions. In this case, they coordinate their actions and exchange information, and a common behaviour can emerge from their interactions that fixes the rules for resources use.

2.1.2 Dealing with complexity

To deal with the complexity of CS, Müller (2004) suggests that the representation of a CS requires:

- the need of multi-scale descriptions, because it minimally implies the articulation of the level of the components, the level of the whole and the level of the underlying environment;
- the multiplicity of view points because the wholes to consider are intrinsically related to the question being asked and therefore give rise to interacting view points (in addition to interacting components!);
- the intricacy of whole and component behaviours both by the reciprocal relationship of the global behaviour and the local behaviours and by the relative autonomy of the global behaviour with respect to the local behaviours;
- the emergence of the whole organisation because of the non-linearity of the underlying interactions.

Then, according to Müller (2004), the representation of CS satisfies at least three levels of representation: the individual, global and underlying environment. The components and the global behaviour influence other. The problem that arises from the Müller's definition is how to represent the macro-level and micro-level and their articulations.

Three sociological approaches to institutions discussed the representation and articulations between the macro and the micro levels (Gilbert, 1995): the methodological holism, the methodological individualists and the methodological constructivism theories. These theories allow to have some ideas how dealing with the macro and micro levels representation and articulations in CS modelling. According to the methodological holism theory, the global level (social institutions and phenomena) is external to the individuals (components) and must be defined explicitly and independently from the individuals compounding the whole system. Durkheim (1895) asserts that:

> *"...The states of the collective consciousness are of a different nature from the states of the individuals consciousness: they are representations of another kind. The mentality of groups in not the mentality of individuals; it has its own laws... To understand the way in which a society conceives of itself and the world that surrounds it, we must consider the nature of society and not the nature of individuals.".*

According to the methodological holism, the individuals' social behaviour should be explained in terms of the positions or functions of these individuals within the social system and the laws which govern it (O'Neil, 1973). The methodological holism is more interested in the macro phenomena than the micro phenomena.

In contrast, the methodological individualists see macro phenomena accounted by the macro level properties and behaviour of individuals (Gilbert, 1995). The methodological individualists is a botton-up emergent-flavoured approach (Amiguet et al., 2003). The representation of a CS according to the methodological individualists theory should only take into account the micro level by assuming that the macro level should arise from the individuals behaviour and interactions.

The methodological constructivism theory asserts that there is a duality between macro and micro phenomena. The humans reproduce the social structure (rules, laws) through their actions. In turn, the social structure constrains and enables the humans actions. Then, structure is at the same time both the outcome of the knowledgeable humans conduct and the medium how conduct occurs (Giddens, 1984). The representation of a CS according to the methodological constructivism theory requires an explicit representation of the macro and micro levels. The macro level properties (rules, laws, etc.) must be expressed explicitly and understandable by the individuals to allow them to reason about their society and act in. That assumes that the individuals have their own behaviour, their own decision model which allows them to reproduce the social structure. But the methodological constructivism theory does not define how the individuals can be expressed at the macro level.

For example, a university is an institution. It has its own norms and rules that govern the behaviour of the humans in the university. The humans know these norms and rules and their behaviour is constrained by these. However, the behaviour of the humans in the university depends on their function (student, administrator, teacher, etc.). The rules in the university are not necessarily the same for all stakeholders. For example, the students have not the same obligations than the teachers. Then, to define how the stakeholders behave in the university, it is necessary to take into account their functions (position) as asserted by the methodological holism. That allows to express how the stakeholders perceive each other and interact among them. But, in order to express how the stakeholders reproduce the society and influence it, it is necessary to take into account their own decision model from the internal point of view. From, what precedes, the representation of an individual in a CS requires to take into account two features: external features expressed at the macro level and the internal features expressed at the micro level. These two kind of features do not exist at the same level of description and must be described explicitly and separately.

2.1.3 Approaches for complex system modelling

Due to their complexity, the analysis of CS is difficult - sometimes impossible - in the real word and requires simulation tools to reduce CS complexity and facilitate their observation and understanding.

> *"When the situation is too complex to be studied analytically it is important to be able to recreate an artificial universe where experiments can be done in a reduced and simulated laboratory where all parameters can be controlled precisely."* (Drogoul et al., 1992).

Three approaches are currently used in CS modelling (Müller, 2004) :

analytical approaches: by analysing the system component by component as advocated by the classical rational approach. In such models, the focus is on the individual behaviours rather than on the interactions;

holistic or systemic approaches: by analysing the system as a whole by isolating aggregated variables and their interactions (rather than the interactions between the components) as is done in most dynamical models as compartment, statistical or eulerian models;

constructivist approaches: by trying to articulate the individual behaviours of the components with the global behaviour of the system as is done in lagrangian dynamical models, individual-based approaches, micro-simulation or multi-agent systems depending on the scientific domain in which such inquiries take place. In such models, the focus is on the interactions rather than on the individual behaviours.

This dissertation is interested in the complex system simulation most specifically in carbon dynamics analysis and representation. We use the constructivist approach specifically the agent-based modelling.

2.2 Simulation

Shannon (Shannon, 1998) defines the simulation as :

> *"the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluating various strategies (within the limits imposed by a criterion or a set of criteria) for the operation of the system."*

This definition of simulation underlines some main concepts of simulation: the *model*, the relation between the *model* and the *reality* and the *experimentation*. The objective of the simulation is to reduce the complexity of the reality through a model which can be used to experiment that is too complex to implement in the reality. As detailed below, simulation allows understanding of system and predicting the state of a system under several scenarios.

2.2.1 Computer simulation for understanding of complex system

Building a model raises the following questions: what factors to take into account? What level of description to chose? What entities and relations to take into account? Then, modelling is an abstraction activity (Amblard et al., 2006) guided by the initial question on the studied system. The choice of variables, of entities, etc. to describe does not depend only on the initial question but also on the modeller's knowledge about the system. In the modelling process, other questions arise and require new observations. The modeller makes new hypotheses which guide new observations. From simulation the modeller tests and validates these hypotheses. The simulation allows underlining the incoherence, incomprehension and the necessity of new observations. The new observations allow the modeller to improve his/her knowledge on the system so that at the end he/she has a better understanding of the system. Then, the computer modelling is a way for the progressive learning about a system.

> *"If the whole process of modelling has succeeded, something will have happened in our head, namely that an understanding of relationships has emerged. We should then be in a position to communicate our insights to others without referring to the model"* Grimm (Grimm, 1999).

Thus, for Grimm, the first added value of a model is to have been built. Then, the computer simulation is considered as a new and intermediate source of knowledge, just between theory and experiment (Varenne, 2001). It allows not only to elaborate knowledge but also to discover knowledge on a system.

The model, once built, becomes a tool, a support for experimentation and the real word observation. For that, Phan (2008) argue that the model is a way to experiment in a *virtual world* the explanatory power of some hypotheses empirically chosen.

In order to underline the advantages of computer simulation in CS understanding, Varenne (2001) summarizes the properties of computer simulation under three thesis: (1) a computer simulation is an experiment, (2) the computer simulation is an intellectual or theoretical tool for the representation of CS and (3) new scientific method in others terms an intermediate between theory and experiment.

2.2.2 Computer simulation for prediction and anticipation

The understanding of a system is not the only purpose of the simulation. The simulation is also used for the prediction and the anticipation of the behaviour of the CS. The objective is to build a virtual world running on a computer in order to predict the state of the real world under several scenarios. The outputs of the model are analysed and compared depending on the input. Using the computer simulation, it is possible to predict what the future state of a system would be, to know the factors which influence a system and take decisions in order to achieve some goals or to avoid some problems.

For example, the IPCC uses computer simulation to predict the global climate change. The objective of IPCC is to inform on climate change trends, consequences and possible mitigation and adaptation state goes. However, the climate change is complex and depends on various factors. Several scenarios are built for the simulations of the global warming. The outputs of the simulations are analyzed to determine the drivers of the global warming and to define the best strategies that would reduce GHG emission and global warming. In this case, the simulation is used not only as a tool for prediction but also as a tool for decision to determine the best policies of the climate regulation. As a support for decision-making, the computer simulation is more and more adopted as a tool for consultation and communication between stakeholders. It is used as a visual support, a tool to help to the elaboration of collective rules of management between stakeholders (Bousquet et al., 2002a, Barreteau et al., 2003).

2.3 Model

Minsky's defines a model as follows:

> *"To an observer B, an object A* is a model of an object A to the extent that B can use A* to answer questions that interest him about A"* (Minsky, 1965).

According to this definition , a model depends on the initial question about a real system. To answer to this question, the modeller must describe the real system by describing only the relevant variables for its understanding. Then, a model is just a simplification of a real system. By including only the relevant variables of the system under studied, a model is more explicit and facilitates the observation of the system:

> *"The advantage of a model is that it can be more explicit, simpler and easier to manipulate than the reality it is supposed to represent"* (Ferber, 1999).

However, a model does not describe only the reality. A model can be an intellectual construction of a virtual phenomenon (Michel, 2004). For the same system, a lot of models exist depending on the objectives of the modeller. A map is an example of a model. For one region, several maps can be drawn, each map providing a particular representation of the region.

2.4 The simulation methodology

Shannon (Shannon, 1998) proposes a methodology to allow the modellers to move from a problem resolution requirement to a final model. For that, he identifies the following steps:

1. Problem definition: clearly defining the goals of the study so that we know the purpose, i.e. why are we studying this problem and what questions do we hope to answer?
2. Project planning: being sure that we have sufficient and appropriate personnel, management support, computer hardware and software resources to do the job.
3. System definition: determining the boundaries and restrictions to be used in defining the system (or process) and investigating how the system works.
4. Conceptual model formulation: developing a preliminary model either graphically (e.g. block diagram or process flow chart) or in pseudo-code to define the components, descriptive variables, and interactions (logic) that constitute the system.
5. Preliminary experimental design: selecting the measures of effectiveness to be used, the factors to be varied, and the levels of those factors to be investigated, i.e. what data need to be gathered from the model, in what form, and to what extent.

6. Input data preparation: identifying and collecting the input data needed by the model.

7. Model translation: formulating the model in an appropriate simulation language.

8. Verification and validation: confirming that the model operates the way the analyst intended (debugging) and that the output of the model is believable and representative of the output of the real system.

9. Final experimental design: designing an experiment that will yield the desired information and determining how each of the test runs specified in the experimental design is to be executed.

10. Experimentation: executing the simulation to generate the desired data and to perform sensitivity analysis.

11. Analysis and interpretation: drawing inferences from the data generated by the simulation runs.

12. Implementation and documentation: reporting the results, putting the results to use, recording the findings, and documenting the model and its use.

2.5 Approaches for complex systems modelling

CS analysis requires modelling tools to deal fully with the complexity. To represent the underlying dynamics of a CS, various modelling techniques have been proposed.

2.5.1 Mathematical modelling

The mathematical modelling is based on the aggregation of variables to describe a system. The mathematical based models treat a system as a whole. Only the global level is represented in such models. They consider that the understanding of the behaviour of whole system allows understanding of the individuals' behaviour. In addition, these models take only into account the quantitative variables. To conclude, the mathematical-based models are too simplified to provide a realistic representation of a CS.

2.5.2 Cellular automate

The Cellular Automate (CA) has been introduced by John von Neuman and Stanislaw Ulam to represent the biological phenomena (Zeigler et al., 2000). It is based on the discretization of space and time. The behaviour of individuals is represented through cells located on a one or multidimensional grid. The cells are connected in a uniform way. Each cell is characterized by a finite set of states and transition rules. The transition rules determine the next state of a cell by taking into account its current state and the states of its neighbours. The transition rules are identical for all cells.

The CA are adapted to a system with organized complexity (Bousquet et al., 2002b) where the individuals have homogeneous behaviours. In addition, the CA assumes that the modeller *a priori* knows all states of the system. In CA, the state of the system depends only on the states of the components (cells) in the system. It is impossible to take into account the external perturbations and their consequences on the system state change. Using CA, it is impossible to deal with complex adaptative and open systems. A CS is not predictable or closed. It is self-adaptive and evolving. According to the external perturbations, the system changes its state and adapts its behaviour.

2.5.3 Individual-based modelling

Individual-based modelling (IBM) has been introduced by Huston et al. (1988) to deal with heterogeneity in ecology simulation. According to Grimm (1999):

> *"Individual-based modelling' refers in the following to simulation models that treat individuals as unique and discrete entities which have at least one property in addition to age that changes during the life cycle.."*

According to Huston in (Bousquet and Le Page, 2004),the IBM is based on the idea that (1) the individual must be taken into account because of his or her genetic uniqueness and, (2) the fact that each individual is situated and his or her interactions are local. IBM provides a framework to represent in the same model, different types of individuals interacting with their environment. Using IBM, it is possible to simulate the spatial dynamics of the individual and their impact on the environment.

The IBM cannot represent how the individuals can be organized in order to form other units. In addition, the IBM is not interested in the individuals' decision-making. The ecosystem management requires integrating human and their activities. The integration of the human activities requires taking into account the individual decision rules, their interactions and the environmental feedback. Human decision making evolves according to the situations, they learn about their environment by taking into account their experiences. Using IBM, it is difficult to deal fully how the individuals make decision, interact among them and learn about their experiences and the strategies of other individuals.

2.5.4 Multi-agent system simulation

Multi-agents system simulation (MAS) is based on the understanding of the global phenomena through the hypothesis defined at individuals and the collective level (Amblard et al., 2006). MAS decompose a system into autonomous agents (Ferber, 1999) interacting at different scales of time and space. The agents evolve in an environment that they can perceive and modify through their actions. They interact between them and make decisions in order to achieve their goals. From their interactions some properties can emerge at the global level influencing the agents' behaviour. Unlike the mathematical models, MAS allow taking into account the articulation between individual and global levels while integrating the underlying environment. The agents in MAS can coordinate their actions to share resources and make decisions. In addition, they adapt their behaviour and learn by taking into account their experiences and the strategies of other agents. MAS are composed of heterogeneous entities. Each type of agent has its own *"model of behaviour"* (Amblard et al., 2006). Using MAS, it is possible to integrate in the same model different types of individuals for a realistic representation of a CS. An agent can be individual as well as other units-such as population or region- interacting at different scales. Thus, the MAS can be used to represent large scale and hierarchical models.

2.6 Conclusion

This chapter allowed to define the properties of the CS and how dealing with their complexity. Then, we showed that dealing with complexity require to take into account (1) a multi-point of view description and (2) the articulations between the macro and micro levels while integrating the underlying environment. The question is how to deal with multi-point of view description both at the macro and micro levels?, how to deal with the articulations between the macro and micro levels?

Three theories in sociology discussed with the macro and micro levels articulations in sociology. Between the different modelling approaches presented in this chapter (mathematical modelling, cellular automota, IBM and MAS), the MAS approach is more relevant to deal with the articulation between the macro and the micro levels as defined by these theories. It allows not only to provide an explicit representation of the macro-level with constraints the micro-level (OCMAS models) but also to define how the macro-level can emerge from the micro-level (AC-MAS models). The next chapter introduces the multi-agents system and presents a review of the models dealing with the macro and micro levels representation.

Chapter 3

Multi-agents system

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3.1 Introduction

The MAS arise from the Distributed Artificial Intelligence (DAI) and artificial life (Ferber, 1999). MAS are based on the distribution of knowledge among autonomous and heterogeneous entities called agents, interacting among them in order to resolve a global problem in a distributed way. Due to its flexibility to integrate heterogeneous, autonomous and adaptative agents and systems, the MAS become more and more a relevant and natural way to represent the CS. Nowadays, the MAS cover many domains: ecology, sociology, economy, etc.

However, building MAS is hard and requires methodologies and tools which guide the designer in the analysis, design and implementation steps. In this purpose, many MAS modelling frameworks have been proposed. Many authors currently use the standard software engineering frameworks as the basis of their proposition. The proposed frameworks use currently two approaches to specify the MAS structure: the Agent-Centered Multi-Agent System (ACMAS) (Drogoul et al., 1995) and the Organisation-Centered Multi-Agent System (OCMAS) (Ferber and Gutknecht, 1998, Hübner et al., 2002). The OCMAS models are more relevant to deal with the complexity than the ACMAS models (Ferber and Gutknecht, 1998, Jennings and Wooldridge, 2000). In Chapter 2, we showed that the CS modelling requires taking into account the macro-level, the micro-level and the underlying environment. The ACMAS models and the OCMAS models differ in the way they deal with the macro-level and micro-level representation. The ACMAS models assume that the macro-level emerges from the micro-level. The macro-level is not explicitly represented. As to OCMAS, they assume that the macro-level exists *a priori* and constraints the micro-level. The OCMAS models provide a flexible framework to deal with the articulations between the macro and the micro levels. In addition, they allow dealing with the multi-point of view description of CS both at the macro and micro levels through the notions of organisation and role.

In this chapter, we define first the main concepts of the MAS and OCMAS approach. In addition, we provide a state of art of the OCMAS models in order to show the advantages and limitations of the OCMAS models in CS modelling and to take the macro level, the micro level and the underlying environment.

3.2 Agent

Ferber (Ferber, 1999) defines agent as a *computing entity* which:

- *is in open computing system (assembly of applications, networks and heterogeneous systems),*
- *can communicate with other agents,*
- *possesses resources of its own,*
- *has only a partial representation of other agents,*
- *possesses skills (services) which it can offer to other agents,*
- *has behaviour tending toward attaining its objectives, taking into account the resources and skills available to it and depending on its representations and on the communications it receives,*
- *is situated in an environment,*
- *is driven by a survival/satisfaction function,*
- *is capable of perceiving its environment (but to a limited extend)*
- *can perhaps reproduce,*

An agent is an autonomous entity, interacting with other agents to share resources, information, to request or provide services. An agent can be viewed as a social entity pursuing one or many goals. The agents in MAS have not necessary the same properties, same decision-making, etc. They are heterogeneous, but they can interact among them to achieve global goals. The interactions take place in an environment. The environment drives the interactions and constrains the agents' behaviour. The agents act on the environment through actions that they carry out in order to achieve their goals. Through these actions, the agents modify their environment. The agents react to the environment change by adapting their behaviour. Wooldridge (1997) define an agent as a software entity which the following properties :

- *Autonomy : agents encapsulate some state (that is not accessible to other agents), and make decisions about what to do based on this state, without the direct intervention of humans or others,*

- *Reactivity : agents are situated in an environment, (which may be the physical world, a user via a graphical user interface, a collection of other agents, the INTERNET, or perhaps many of these combined), are able to perceive this environment (through the use of potentially imperfect sensors), and are able to respond in a timely fashion to changes that occur in it,*
- *pro-activeness : agents do not simply act in response to their environment, they are able to exhibit goal-directed behaviour by taking the initiative,*
- *social ability : agents interact with other agents (and possibly humans) via some kind of agent-communication language and typically have the ability to engage in social activities (such as cooperative problem solving or negotiation) in order to achieve their goals.*

3.3 Architecture of Agents

To react to the environment changes, the agents must have the capabilities to determine the actions to carry out according to the environment state. Their decision-making depends on the perception they have on their environment. For that, they observe the environment and generate a perception. According to this perception, the agents determine the actions to carry out. Then, the decision-making of an agent can be divided in *perception*, deliberation and *action*. But, how to tell to agents to carry out a specific action according to their perception?

> *"We do not (usually) build agents for no reason. We build them in order to carry out tasks for us. In order to get the agent to do task, we must somehow communicate the desired task to the agent. This implies that the tasks to be carried out must be specified by us in some way. An obvious question is how to specify those tasks: how to tell the agent what to do it"* (Wooldridge, 2002).

The actions generation by the agents depends on their internal architecture. According to their architecture, we distinguish three types of agents: the reactive agents, the Belief-Desire-Intension (BDI) agents and the hybrid agent.

3.3.1 The reactive agents

The reactive agents have a partial representation of their environment. Their decision making is based on the local information and their current state. They have not explicit goals and react according to their perception on their environment. The reactive agents cannot learn about their experience. The models based on reactive agents require a large number of agents and are easy to implement. In these models, it is assumed that the global behaviour of the system emerges from the agents' interactions and the architecture of the agents may not necessarily be complex to exhibit intelligent behaviour to achieve complex tasks. For example, the MANTA model is based on reactive agents. This model studies the emergence of labour division within a society of primitive ants (Drogoul et al., 1995). The agents (ants) interact among them through the environment. From their interactions, a collective behaviour emerges where each agent is specialized in the accomplishment of some tasks.

3.3.2 The cognitive agents

The objective of the cognitive architecture is to build rational agent. Unlike reactive agents, cognitive agents have explicit goals. They have a partial representation of their environment and others agents. They reason about their goals, the representation they have on their environment and make decisions. In addition, they have an adaptative behaviour. They learn about their experience and anticipate the environment change. The Believe Desire Intension(BDI) (Rao and Georgeff, 1992) architecture is an example of the cognitive architecture. The BDI architecture is based on three main notions: *believe*, *desire* and *intention*. The BDI agents make decision according to their perception and their believe on the environment. Then, from their perception, they revisit their believe. Depending on their intensions and believe, they determine a plan of actions to execute in order to achieve their goals.

3.3.3 The hybrid agents

The objective is to build agents capable of reactive and proactive behaviours (Wooldridge, 2002). The architecture of hybrid agents is specified through a set of interacting software layers. Each layer provides a reactive or proactive behaviour. The layers interact among them through information and control flows. Two types of hybrid agents architectures exist:

1. *Horizontal architecture*: each layer is connected to a same sensor input and an action output. According to the inputs, each layer generates actions suggestions to carry out. A mediator manages the information and controls flows between layers in order to ensure a coherent behaviour of the agent.

2. *Vertical architecture*: the sensor input and the action output are connected at most one layer. The information and control flows pass sequentially through the layers. According to the management of information and control flows, two types of vertical layer exist: the *one-pass architecture* and the *two-pass architecture*. In the *one-pass architecture*, the information and control flows sequentially each layer, until the final layer generates actions.

In the *two-pass architecture*, the information flows from the *layer 1* to *layer n* and the controls flows from *layer n* to *layer 1*.

3.4 Multi-agents systems

Ferber (Ferber, 1999) defines MAS as a system comprising the following elements:

1. *An environment, E, that is, a space which generally has a volume.*
2. *A set of objects, O. These objects are situated, that is to say, it is possible at a given moment to associate any object with a position in E. These objects are passive, that is, they can be perceived, created, destroyed and modified by the agents.*
3. *An assembly of agents, A, which are specific objects ($A \subseteq O$), representing the active entities of the system.*
4. *An assembly of relations, R, which link objects (and thus agents) to each other.*
5. *An assembly of operations, Op, making it possible for the agents of A to perceive, produce, consume, transform and manipulate objects from O.*
6. *Operators with the task of representing the application of these operations and the relation of the world to this attempt of modification, which we shall call the laws of the universe.*

Nowadays, the MAS establish themselves more and more as essential tool for complex systems modelling.

3.5 The Notion of Environment

The agents are embedded in an environment in which they drive their activities. The agents perceive the environment and modify it in order to achieve their goals. The agents' perceptions and actions are controlled by the environment. The environment constitutes the support of the agents' communications and provides conceptual model which allows them to reason about the environment and make decisions. The place of the environment in CS requires paying a particular attention to the notion of environment and its specification in MAS.

The notion of environment is ambiguous in the MAS community. Weyns et al. (2005) identify three meanings of environment in MAS community. Sometimes, the environment is a logical entity of a MAS in which the agents and others object/resources are embedded. Sometimes, the notion of environment is used to refer to the software infrastructure on which the MAS is executed. Sometimes, environment even refers to the underlying hardware infrastructure on which the MAS runs. In order to disentangle the confusion, Weyns et al. (2005) propose a 3-layer model for MAS (Fig.3.1).

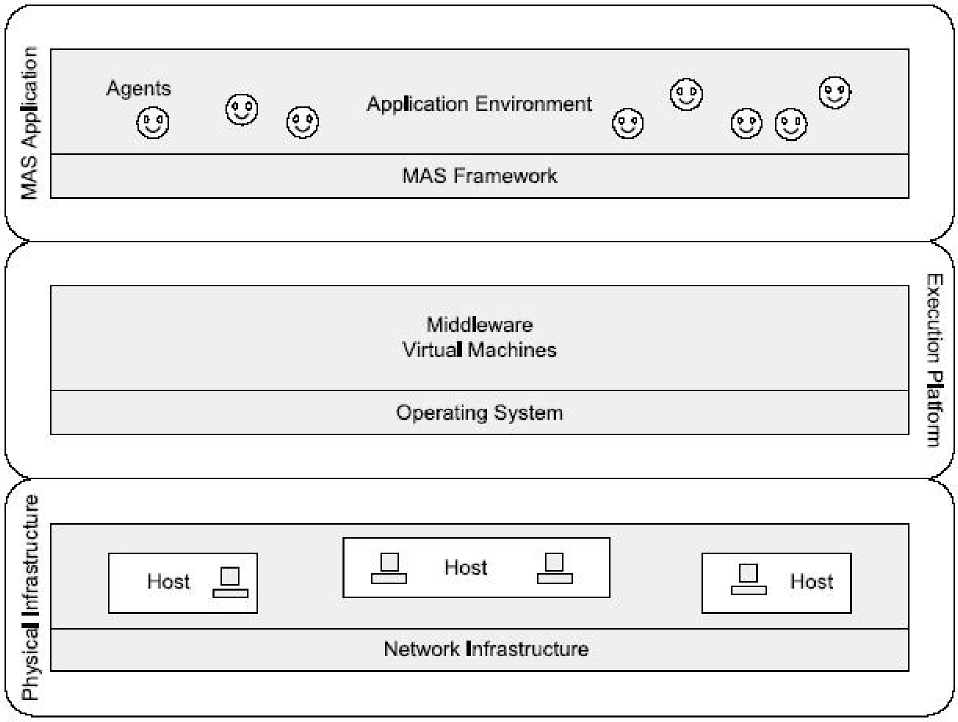

Figure 3.1: 3-layer model for MASs

The responsibilities of the environment make it an essential component of MAS. Then, the environment must be explicitly defined as first-class entity (Weyns et al., 2005) in order to fulfil its responsibilities. The environment specification in MAS, requires taking into account some concerns that (Weyns et al., 2005) categorize into two types of concerns: the concerns related to the structure of the environment and the concerns related to the activity in the environment.

3.5.1 Concerns related to the structure of the Environment

They are related to structural features of the environment: structuring, resources and ontology. These features allow agents understanding their environment.

structure: the environment defines the relationships among agents and the environment objects. It defines the rules under which these relationships exist and evolve. The structure of the environment can be spatial, organisational or a mediating entity.

Resources: besides the agents, an environment typically comprises different types of objects or (logical) resources. The environment may define the laws of access to the resources depending to the domain in interested.

Ontology: an environment must specify an ontology that provides a conceptual representation of the domain at hand in order to allow to agents to understand their environment. Ontology must cover the structure of the environment as well as the observable characteristics of objects, resources and agents, and their interrelationships. The cognitive agents reason about their environment and interpret it using the ontology while it is encoded in reactive agents' internal structure.

3.5.2 Concerns related to the activity in the environment

The previous concerns of environment specification in MAS deal with how to allow agents to understand their environment and access to the resources. Other responsibilities of the environment are to allow agents to drive coherently their activities in the system. These responsibilities are related to management of the agents' communication, their perception and the environmental processes.

Communication: the environment supports and mediates the agents' communication.

Actions: the agents perceive and modify their environment through the actions they achieve. However, the agents cannot directly modify the environment state. The environment controls its own state and evolves its state to the reactions to the agents' actions.

Perception: the agents make decision according to their perception. The agents' perceptions depend on their capabilities to observe their neighbourhood and the environmental properties. In order to allow agents to perceive their environment and make decision, the environment may define the perceptual laws according to the agents' capabilities and the environmental properties.

Environmental processes: the environment is an active entity which its own processes that can change its own state independently of the activity of the embedded agents.

3.6 The notion of organisation

3.6.1 Definition

The organisation in one of the essential concepts of OCMAS. The organisation reduces the complexity and makes easer a CS understanding. According to Booch in (Jennings, 2000) the organisation definition allows to tackle the complexity in two ways.

> *"Firstly, by enabling a number of basic components to be grouped together and treated as a higher-level unit of analysis (e.g., the individual components of a subsystem can be treated as a single coherent unit by the parent system). Secondly, by providing a means of describing the high-level relationships between various units (e.g., a number of components may work together (cooperate) to provide a particular functionality)".*

The notion of organisation is ambiguous in MAS community. Various definitions have been proposed. We are going to provide some definitions according to the elements we aim to underline. In CS modelling, the scientists are interested to the description of the elements of the system, the nature of their relationships, the system organisation and how this organisation evolves in the time. According to (Morin, 1997):

> *"An organisation can be defined as an arrangement of relationships between components or individuals which produces a unit, or system, endowed with qualities not apprehended at the level of the components or individuals. The organisation links, in an interrelational manner, diverse elements or events or individuals, which henceforth become the components of the whole. It ensures a relatively high degree of interdependence and reliability, thus providing the system with the possibility of lasting for a certain length of time, despite chance of disruption."*

The organisation describes not only the relationships between components but also how they interact and achieve their objectives. In other terms the organisation defines how the components behave individually in order to achieve a global behaviour which can emerge from the components interactions. In addition, the organisation ensures the coherency and the adaptability of a system. Gasser (Gasser, 1992) suggests that:

> *"An organisation provides a framework for activity and interaction through the definition of roles, behavioral expectations and authority relationships (e. g. control)."*

This definition introduces the notion of interactions which take an important place in organisation description. Ferber (Ferber, 1999) underlines the relation between interaction and organisation:

> *"The interaction forms the basis of the constitution of organisations, and at the same time interactions assume the definition of space, and generally of a pre-established organisation, within which they can take place."*

In addition to the notion of interaction, the Gasser's definition introduces the notion of roles. The role provides an abstract description of agent's behaviour. A role describes the constraints that an agent will have to satisfy to obtain that role, the benefits that an agent will receive in playing that role and the responsibilities associated to that role (Ferber, 1999). The roles are in relation between them and allow the agents to interact. The relations between the roles define the structure of an organisation. However a role is closed to an organisation. Then, only agents playing roles in the same organisation can interact among them. Wooldrigde et al. (2000) proposed the following definition:

> *"We view an organisation as a collection of roles, that stand in certain relationships to one another, and that take part in systematic institutionalised patterns of interactions with other roles."*

From what precede, we can conclude that the description of the structure of system will consist in the definition of organisation, the roles and their relationships, the interactions patterns, the agents, etc. However, the organisation definition depends on the designer's objectives. He/she defines the organisations according according to his/her points of view on the system at the global level. By considering an organisation as a point of view, Muller (2003) suggests that

> *"A CS can be described as a set of organisations that are all points of view on the system."*

Then, a role can be viewed as a point of view of the designer on the components of the studied system. The roles played by an agent represent so various points of view on the agent.

The organisation description requires taking into account two levels of description: the organisation level and the agent level (Ferber, 1999). The organisation level is what persists when components or individuals enter or leave an organisation. The organisation level description is based on the specification of the structures and pattern of activities among agents based on abstraction such as groups, roles, interactions, protocols, authority constraints between roles, etc.

(Helleboogh et al., 2006). The organisation level describes the "what" and not the "how" (Ferber et al., 2003) . The organisation level imposes a structure of the pattern of agents' activities, but does not describe how agents behave. In addition, the organisation level is not interested to the agents' mental issues. The agent level is a particular instantiation of the organisation level.

3.6.2 The general principles of organisation-centered

The organisational design may respect to some principles explained in (Ferber et al., 2003) as following:

Principle 1: The organisational level describes the "what" and not the "how". The organisational level imposes a structure into the pattern of agents' activities, but does not describe how agents behave. In other terms, the organisational level does not contain any "code" which could be executed by agents, but provides specifications, using some kind of norms or laws, of the limits and expectations that are placed on the agents behaviour.

Principle 2: No agent description and therefore no mental issues are provided at the organisational level. The organisational level should not say anything about the way agents would interpret this level. Thus, reactive agents as well as intentional agents may act in an organisation. In other words, ant colonies are as much organisations as human corporations. Moreover, seen from a certain distance, or using an intentional stance it is impossible to say if the ants or the humans are intentional or reactive. Thus, the organisational level should get rid of any mental issues such as beliefs, desires, intentions, goals, etc. and provide only descriptions of expected behaviors.

Principle 3: An organisation provides a way for partitioning a system, each partition (or group) constitutes a context of interaction for agents. Thus, a group is an organisational unit in which all members are able to interact freely. Agents belonging to a group may talk to one another, using the same language. Moreover, groups establish boundaries. Whereas the structure of a group A may be known by all agents belonging to A, it is hidden to all agents that do not belong to A. Thus, groups are opaque to each other and do not assume a general standardization of agent interaction and architecture.

However, most existing organisation-centered models do not take into account these different general principles. These models do not provide a flexible way to describe independent and reusable organisational structure of the MAS. In this thesis, we intend to take into account the general principles of organisation centered models. In our proposition, the organisation level is defined without taking into account the entities level. But, in our proposition, the notion of organisation does not design a partioning of a system into groups. An organisation defines a point of view on a system at the global level and provides an abstract description of the groups. The structure of a model is described through a set of organisations. In addition, we are not interested in the notions of norms and verifications.

3.7 Multi-agents systems and complex systems modelling

> *"In most cases, agents act to achieve objectives either on behalf of individuals/companies or as part of some wider problem solving initiative"* (Jennings, 2000).

From this point of view, an agent can be viewed as a decomposition of a problem into controllable sub-problems. The assembly of the agents form the overall functionality of the system. The decomposition reduces the complexity and makes easer the understanding of the underlying dynamics of a CS:

> *"when the problems are too extensive to be analysed as a whole, solution based on local approaches often allows them to be solved more quickly"* Ferber (1999).

CS are self-adaptative and self-organised. To understand such systems, it is necessary to exhibit some organisational principles. The organisation of such systems must be explicitly defined. MAS allow an explicit representation and management of the organisation (group formation, maintaining and disbanding) of a system (Fig.3.2). A system is viewed as a set of groups interacting through entities playing roles (Ferber and Gutknecht, 1998, da Silva and de Lucena, 2007). The organisations define the laws governing the agents behaviours (Dignum, 2004, Esteva et al., 2001). The agents in MAS can reason about the organisation structure and evolve their behaviour. From their interactions, a collective behaviour can emerge and constraints the agents behaviour. Then, using MAS it is possible to express how the macro-level and the micro-level influence each other.

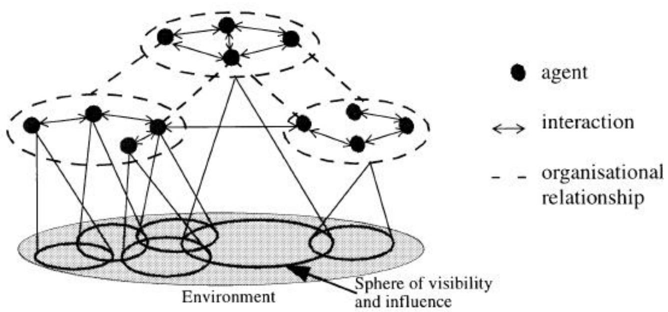

Figure 3.2: MAS organisation (Jennings, 2000)

A CS exists at different scales of description. A scale can be a part of another scale and so on. For example, a Multinational company (Fig.3.3) is a multi-scale system (Giret and Botti, 2004). It is composed of different National companies among different countries. Each National company evolves in a national market and interact with the other national companies. Each National company is governed both by the national and the Multinational rules and norms. The Multinational is also governed by the international agreements among different countries, such as Union European, UEMOA, etc. Such systems require a hierarchical and multi-scale representation. An agent does not represent only an individual. MAS provide mechanisms for building hierarchical and large scale systems. An agent can represent an atomic agent or unity (organisation or MAS) (Fig.3.4) composed of other agents and unities in interactions at the same scale of description (Gaud, 2007, Giret and Botti, 2004). Using MAS, it is possible to integrate several MAS models in order to form a high level system. Each MAS model behaves as a single agent interacting with other MAS models at the same level.

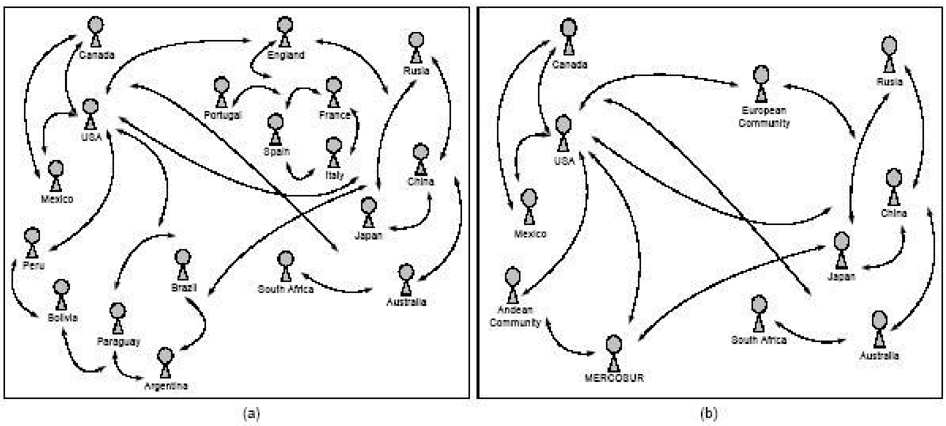

Figure 3.3: Example of Multi-scale system (Giret and Botti, 2004)

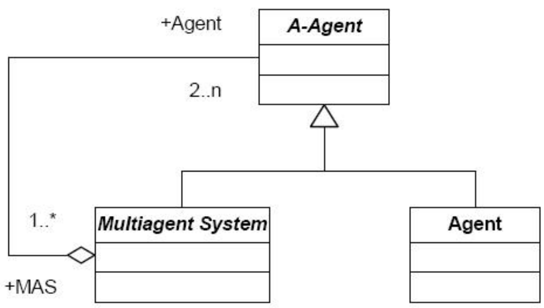

Figure 3.4: Abstract recursive agent (Giret and Botti, 2004)

Nowadays, the computer systems are more and more distributed and heterogeneous. These systems are very evolutionary and have an unpredictable behaviour. The increase in the size of these systems implies a loss of control where the risk of unreliability (Gutknecht, 2001). The autonomy of agents, their ability to make decision about the interactions and the structure of system at run-time and the ability of MAS to integrate heterogeneous agents in a same model make MAS more relevant than other software engineering techniques to develop complex and distributed systems (Jennings, 2000, Wooldridge, 1997).

As noticed previously, the environment takes an important place in CS modelling. MAS propose framework to integrate environment, its relations with the agents and feedbacks on the agents' behaviour. The environment mediates the agents communication, supports their physical actions and resources. The agents perceive their environment and transforms it trough their actions.

Due to its flexibility, the MAS become more and more a sustainable tool for CS modelling in many domains: sociology (Amblard and Ferrand, 1998, Gilbert, 1995, 2004), ecosystem management (Matthews et al., 2007, Bousquet and Le Page, 2004, Berger, 2001, Parker et al., 1993), economy (Axtell, 2000), etc.

However, if many authors argue that MAS provide flexible framework in CS modelling, we must know that the MAS building is hard. They require methodologies and tools to help the designers in building the models.

3.8 Methodology, Meta-model and Language

We build MAS to resolve a specific problem. The problem which arises from the model building is how to go from the problem requirement to the final product. For that, the designer needs a methodology. The methodology defines the processes and provides tools for the analysis, design and implementation of a model.

> *"A methodology is a collection of methods covering and connecting different stages in a process. The purpose of a methodology is to prescribe a certain coherent approach to solving a problem in the context of a software process by preselecting and putting in relation a number of methods."* (Ghezzi et al., 1991).

However, methodology typically starts from a meta-model identifying the basic abstraction to be exploited in development (Cernuzzi et al., 2005). A meta-model can be viewed as a model which provides a particular representation of a system and can be used to define specific models. In others words, a meta-model is a model of model with a high level of abstraction. Kleppe et al. (2003) define the meta-model as follow:

> *"A meta-model is an explicit model of the constructs and rules needed to build specific models within a domain of interest "*

A meta-model is strongly linked to a domain. The elements of the meta-model must be understandable by the stakeholders of this domain. The stakeholders may agree on the elements constituting a system and have the same meaning on these elements. For example, the UML meta-model provides notations to specify a system with object-oriented meaning. The object-oriented designers have the same meaning, same representation of the elements making an object-oriented program. Then, a meta-model is a consensual model. For that, Bézin (2005) defines a meta-model as a:

> *"... formal specification of an abstraction, usually consensual and normative. From a given system, we can extract a particular model with the help of a specific meta-model."*

A meta-model is used at all stages of the design process. For example, to build a system with OO meaning, the designers use the UML meta-model at the analysis, designing and the implementation stages to create a specific model. Using the UML meta-model, a methodology will provide guide to analyze, to design and to implement a system. According to Bernon (Bernon et al., 2005),

> *"the process of designing ... consists of in instantiating the system meta-model that the designers have in their mind in order to fulfill the specific problems requirements."*

From what precedes, a meta-model is a key element of a methodology. However, the description of a meta-model requires a formal description. A meta-model acts as precisely defined filter expressed in a given formalism (Bézin, 2005). Many languages are usually used to describe a model: textual notion, XML, graphical notation such as UML. Today, UML is the most commonly used language.

Many methodologies have been proposed in order to deal fully with the MAS building: Ingenias (Pavon and Gomez-Sanz, 2003), Tropos (Bresciani et al., 2004), ADELFE (Bernon et al., 2002), Message (Evans et al., 2001), Aspects (Gaud, 2007) etc. Each methodology intends to resolve a specific problem of MAS building. For example, ADELFE (Bernon et al., 2002) provides a methodology and a meta-model for the self-adaptative and self-organizing systems specifications; Mase (Wood and DeLoach, 2000) is a complete methodology allowing the development of heterogeneous systems; Aspects (Gaud, 2007) concerns MAS and Holonic MAS building. The language used by most methodologies is based on the extension of the UML meta-model such as

AUML (Odell et al., 2000), AML (Cervenka and Trencansky, 2005, 2004), MAS-ML (da Silva and de Lucena, 2007), etc.

The MAS methodologies and applications show the place of the standard software engineering technique frameworks in MAS development. If the software engineering techniques lack to take into account the MAS properties, they constitute a basis for the MAS methodologies proposition. For that, Oren Etzioni in (Wooldridge, 1997) pretends that,

"agents are more a problem of computer science and software engineering than AI."

But, the MAS methodologies are not limited to the software engineering frameworks use. They contribute to the resolution of problems that the software engineering cannot take into account.

3.9 Review of the organisation-centered models

The OCMAS approach is the background of this study. It is necessary to provide a review of this approach in order to underline their advantages and limitations in CS modelling with regard to the purpose of this study.

Organisation is a main concept of the OCMAS approach. An organisation represents a point of view on a system at the global level. To provide a flexible way for multi-points of view description, an OCMAS model must allow a multi-organisational representation. In our study, we assume that the organisation structure - defining the macro level - must be explicitly defined without any assumption on the agent level (micro-level). For that, the organisation structure must be defined separately and independently from the agent structure. The agents behave in an environment that they can perceive and modify. Their perception on the environment depends on their place - defined by the roles they play- in the system. The way in which the agents perceive their environment through their roles must be expressed by integrating environment with organisation. The environment integration in organisation allows defining the nature of relations of interactions between objects and agents independently from their nature. This state of art of OCMAS models is interested in :

- the multi-organisational specification for a multi-point of view description
- the explicit representation of organisational structure and its genericity
- the capacity of the OCMAS models to specify the organisational structure without any assumption on the agent level,

- the genericity of the organisation structure
- the environment integration with organisation in order to provide a flexible way to describe explicitly the interactions between the environment and the entities embedded in it.

3.9.1 The Gaia model

Gaia (Wooldrigde et al., 2000) aims to propose a methodology for the analysis and design of agent-based system. *"Gaia is concerned with how a society of agents cooperates to realise the system-level goals and what is required of each individual agent in order to do this"*. The agent-based system building is showed as a process of organisational design. The Gaia methodology is divided in two parts: analysis and design stages.

Analysis: the objective of the analysis stage is to define the abstract structure of the system. Two models are defined at this stage:

1. The roles model: identifies the roles in the system in order to describe the organisation structure. A role is characterized by:
   - a set of responsibilities specifying the types of resources the role can use.
   - a set of permissions specifying what the role able to do, in other terms the functionalities of the role.
   - a set of protocols specifying the interactions between the roles.
2. The interactions model: identifies the interactions link between the roles.

Design: The objective of the design is to transform the models of the analysis stage in order to implement the agents. Three models derive from the design stage:

1. the agents model: describes the types of agents and their instances
2. the services model: describes the aim services for the roles realisation
3. the acquaintances model: describes the communication link among agents.

The Gaia model does not take into account the MAS implementation and says nothing how to move from design stage to the implementation stage. Also, it does not provide an explicit definition of organisation and does not take into account the multi-organisation representation. The structure of a system with Gaia is static, the agents cannot enter and leave roles dynamically. The notion of role appears only at the analysis stage. At the design stage, Gaia does not take into account the representation of role. In addition, a role type defines the expected function of one type of agent. To finish, the Gaia model does not deal with the environment representation. In our proposition, we assume that a role describes the function of many types of entities and a role can be played in different ways by two types of entities. The organisational structure is dynamic and takes into account the environment objects representation.

3.9.2 The AGR model

The Agent-Group-Role (AGR) model (Ferber and Gutknecht, 1998) is a generic meta-model for the building of complex systems. The AGR model intends to deal with modularity, heterogeneity, security and interoperability in the MAS implementation. The authors think that *"considering organisational concepts, such as groups, roles, structures, dependencies, etc. as first class citizens, and relating them to the behaviour of agents is a key issue for building large scale and complex systems, and resolves all the previous problems in a very clear and efficient manner"*.

AGR uses three mains concepts to describe a MAS structure: group, role and agent (Fig. 3.5). A group in AGR is a set of agents interacting through roles. A role defines an abstract function of an agent in a group; it is closed to a group and can be played by several agents. Only agents sharing the same group can communicate. Unlike Gaia, the structure of AGR supports simultaneously several groups and the agents can enter and leave dynamically the groups by playing or leaving roles.

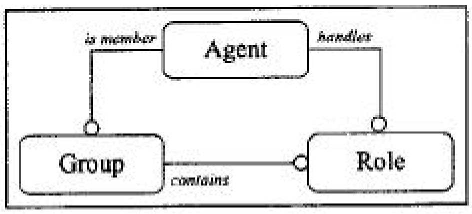

Figure 3.5: The concepts of AGR

As limitations, the AGR model has a very limited expressiveness and offers few concepts for the design of complex systems. The roles are only represented in the implementation stage as labels. The structure of the role is strongly linked to the structure of agent. In consequences:

- AGR does not allow the verification of roles playing. The verification is the responsibility of the designer.
- the AGR implementation (Madkit) does not provide a clear distinction between the individual structure and the organisational structure..
- AGR lacks of modularity and reuse of organisation structure.

As Gaia, AGR does not deal with environment representation. An extension of AGR has been proposed by Ferber et al. (2005) in order to integrate the physical environment with environment.

3.9.3 Parunak and Odell model

Parunak and Odell (Parunak and Odell, 2002) had proposed three extensions of the AGR model (Fig.3.6):

1. Role: roles are defined as recurrent pattern of dependencies and actions.
2. Environment: In AGR, a group is just a collection of agents playing roles. In the Parunak and Odell proposition, a group includes environment through which the agents interact. An environment is represented as a social component of a group.
3. Group: Unlike AGR, a group can play roles in higher level group. Considering group as an agent playing roles and interacting with others agents, the authors take into account the holonic dimension.

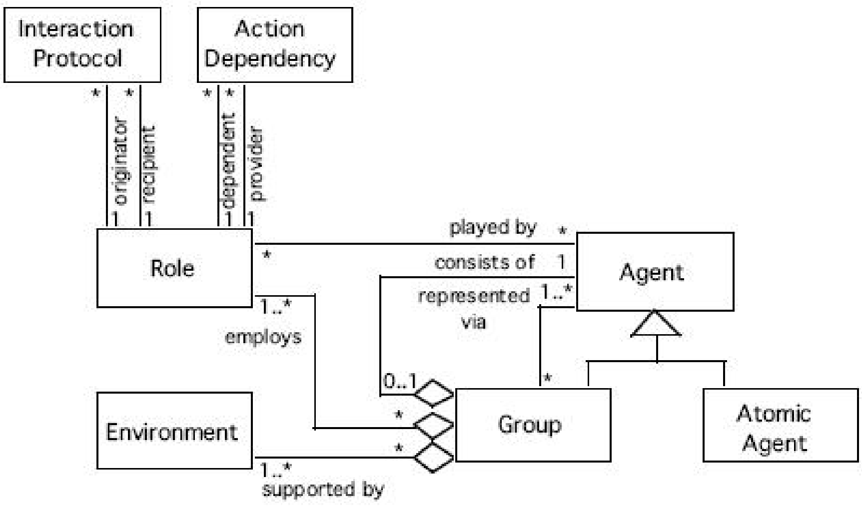

Figure 3.6: AGR extensions

To help the designer in the analysis, specification and design of MAS, some UML conventions and AUML extensions have been proposed.

3.9.4 Hilaire's model

Hilaire (Hilaire et al., 2000) had proposed a framework for organisational specification. Three aims concepts define the meta-model of the Hilaire's model:

1. *Role* defines an abstract behaviour of agents (Fig. 3.7).

Role

behavior

$attributes : \mathbb{P}\, Attribute$
$stimulus : \mathbb{P}\, Event$
$actions : \mathbb{P}\, Action$

Figure 3.7: Role

2. *Interaction* defines the communication link between two roles in a context (Fig. 3.8).

Interaction

$orig == first\ roles$
$dest == second\ roles$

$roles : Role \times Role$
$content : Event$
$\forall\, e \in msg \bullet$
$(e \in (dest.stimulus)$
$\wedge (e \in orig.actions))$

Figure 3.8: Interactions

3. *organisation* describes a social structure. It is defined by a set of roles and their interactions (Fig. 3.9).

Organization

behavior

$roles : \mathbb{P}\, Role$
$env : \mathbb{P}\, envRole$
$interactions : \mathbb{P}\, Interaction$

$\forall\, i \in interactions \bullet (i.orig \in roles \wedge i.dest \in roles)$

Figure 3.9: Organisation description

A multi-formalism approach has been used (1) to make easier and more natural the specification of MAS and (2) to take into account fully the functional and reactive aspects of MAS. This multi-formalism is based on a combination of Object-Z and StateChart formalisms.

The Hilaire's framework makes easier MAS decomposition and understanding. In addition, it provides more expressiveness and the possibility to take into account role inheritance. The environment is represented in the interactions through the notion of *environmental role* . The *environmental role* defines a part of environment with which other roles interact.

But the organisational structure is static. The architecture of the agents is just a collection of roles. The roles describe both the agents' mental state and behaviours. This framework does not allow a clear distinction between the agent structure from the internal and the external point of view. Other limitations of the Hilaire's proposition are that the meta-model does not take into account a clear specification of the different levels of abstraction in MAS specification.

3.9.5 The MOCA model

The MOCA model (Amiguet et al., 2003) deals with how agents can play multiple roles while guaranteeing the system and agent coherency. The MOCA model allows to associate to role playing, a recurrent pattern of individual behaviours while allowing the organisation dynamics. The MOCA structure is based on the role-based and component-based approaches. It provides two levels of description: the *descriptive level* providing the abstract description and the *executive level* describing the agents level. Each level is defined by six main concepts. These concepts can be divided into two categories from an agent point of view (Fig. 3.10). The first category describes the agent's internal properties and the second category describes the agent's external properties.

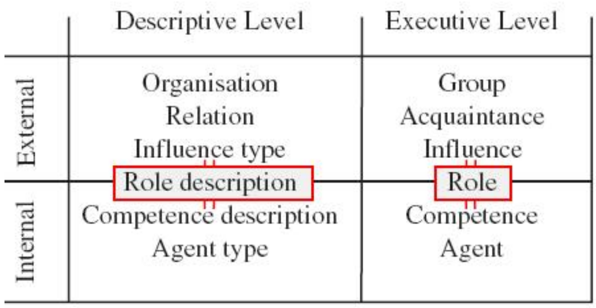

Figure 3.10: The MOCA concepts

To play a role, an agent has to provide the competences required by the role. A competence defines the capability to provide some services. A role can also provide additional competences to agents. Then, when an agent plays a role, it acquires the competences of the role. The structure of an agent in MOCA, is a set of components (roles with competences) that can be added or removed dynamically. A mechanism manages the components and their interactions: the MGC module.

The MOCA includes an organisation which manages the organisational dynamics: *Management Organisation*. The *Management Organisation* has three role descriptions:

1. *YellowPages* manages the list of organisations and groups.

2. *Manager* manages the acquisition of roles by the agents in a specific group. It includes mechanism to verify if an agent has the capabilities to play the requested role.

3. *Requester* asks *YellowPages* about existing groups and organisations and asks for the instantiation of a new group from a given organisation. It can also ask a manager to enter an existing group.

MOCA defines group, role as first class entities. The MOCA model increases the reusability and modularity of organisation. The two levels of description (descriptive and executive) allow implementation of dynamic and evolving systems and the verification of a MAS coherency.

But, as AGR, MOCA does not deal with the environment representation. In addition it sets strict constraints on roles implementation (Gaud et al.). A role defines an effective behaviour of an agent and its dynamics is specified by a statechart. Then, the MOCA organisation level defines how the agents behave. A role describes both (1) the external features allowing an agent to be in relation with others agents and (2) specifies the internal behaviour of the agent. The role specification decreases the independence between organisational structure and the agent structure. In addition, it is impossible for two types of agents to play the same role in different ways.

3.9.6 The AGRE model

AGRE (Ferber et al., 2005) is an extension of AGR which takes into account both the social and the physical environment. AGRE is based on the idea that the agents are situated in domains called spaces (Fig.3.11). A space may be physical (area) or social. The physical space is represented by areas and the social space is represented by the AGR group. The agents manifest in spaces through modes. *Role* and *Body* are considered as modes specifying agent manifestation respectively in organisation and physical environments. Two types of world are defined: (1) the *social world* composed by sets of groups and (2) the *physical world* formed by a set of areas. An agent may belong simultaneously to a social world and to a physical world. In the social world, an agent can play several roles and belong to several groups. In the physical world, an agent can have only one body. It is assumed that an agent cannot live in two different places at the same time unless two areas overlap.

Unlike most OCMAS models, the AGRE model allows explicit representation of the environment in the MAS structure. Also, it is possible to represent simultaneously several environments in a same system. But in AGRE, it is impossible to define the perception of an agent on its

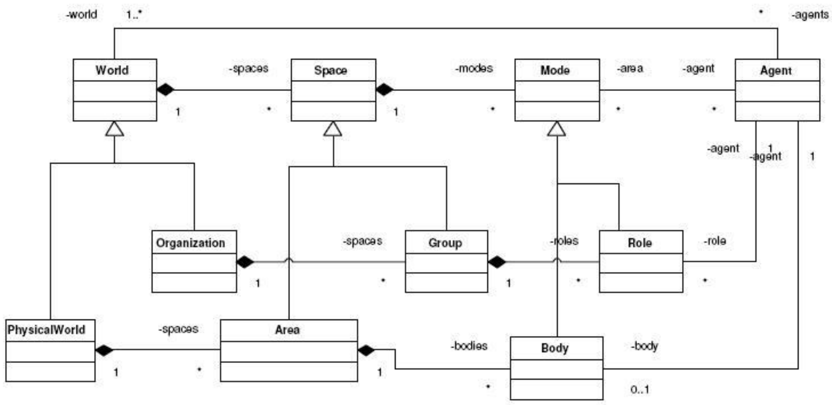

Figure 3.11: The UML meta-model of AGRE at the concrete level

environment through its roles. In some context an agent perception on its environment depends on its social status that is necessary to take into account in organisation structure.

3.9.7 The Cassiopeia model

The Cassiopeia method (Collinot and A., 1998) *"is primarily a way to address a type of problem solving where collective behaviours are to be put into operation through a set of agents"*. Cassiopeia considers the design of MAS in terms of the agents design with three levels of behaviour: *elementary* behaviours, *relational* behaviours and *organisational* behaviours. The Cassiopeia method proceeds in three phases that include the local and global points of view. Each phase concerns the specification of a level of agents' behaviour.

Specification of elementary behaviours: The objectives of this step are:

- the identification of elementary behaviours allowing agents to achieve collective tasks.
- the identification of the types of agents. The elementary behaviours previously identified define the local behaviours of agents. At this step, the designer is not interest in the interactions description.

The specification of relational behaviours: the objective is to describe the relationships and interactions among agents. The designer may define (1) the external dependencies (*influences*) among agents in order to specify the structure of organisation, the reaction of agents to the external influences (according to the global point of view) and (2) the dependencies between the elementary behaviours (local point of view).

The specification of organisational behaviours: the objective of this step is to specify the organisational dynamics. This step consists to define the behaviours allowing the agents to form, to maintain and to dissolve groups according to the goals to achieve.

The Cassiopeia method allows to designer to deal efficiently with both the local and global views by separating the behaviours relevant to the domain (elementary behaviours) from the ones relevant to the agents organisation (relational and organisation behaviours). In addition, Cassiopeia method provides more flexibility in the means where it provides homogeneity in the use of conceptual abstractions (roles, organisation, and influences) from the analysis step to the implementation step. But in Cassiopeia, role playing is not dynamic. Also, the groups are built to achieve a goal. If a group is formed, the agents do not know the type of the created group.

3.9.8 The Moise+ model

The Moise+ (Hübner et al., 2002) is an organisational model for Multi-Agent Systems based on notions like roles, groups, and missions. The Moise+ is an extension of Moise (Hannoun et al., 1999, 2000). It allows building MAS where the agents can collaborate to resolve global goals. The specification of MAS with Moise+ is based on three aspects: the structural aspect, the functional aspect and the deontic aspect.

The structural aspect: defines the agents' relations through the notion of roles and links. It structures a MAS along three levels:

1. the individual level: defines the organisational roles;
2. the social level: defines the relationships between roles. The relationships between roles are defined through three types of links: communication, authority and acquaintances links.
3. collective level: describes the organisational structure.

the functional aspect: describes how a MAS usually achieves its global goals through the definition of the SCH (Social Schema). The SCH is a decomposition of the global goal into sub-goals. The sub-goals are distributed along missions. Then, when an agent accepts a mission, he may achieve the goals associated to the mission.

the deontic aspect: describes the relationships between the structural and the functional dimensions. The deontic aspect defines the role missions and obligations.

The Moise+ model provides a flexible way to describe the structure of MAS. It allows describing explicitly and separately the structural and the functional dimensions of the MAS and to integrate them into a coherent and flexible way through the deontic dimension. By separating the structural dimension from the functional dimension, the Moise+ allows separating the "what" represented by the structural aspect from the "how" represented by the functional aspect. But, the "how" achievement depends on the roles, then by the organisational level.

As other limitations, Moise+ does not describe the interactions between agents and does not describe the structure of the agents. In addition, the model does not describe how the agents enter and leave the groups and roles.

3.9.9 The Mascaret model

MASCARET (Multi-Agent Systems to simulate Collaborative, Adaptive and Realistic Environments for Training) (Buche et al., 2004) *"aims at organizing the interactions between agents in virtual environment and provides them abilities to evolve in this context"*. The MASCARET model uses the concepts of organisation, role, agent and BehaviourFeature to define the MAS structure (Fig. 3.12). The roles describe the responsibilities of agents in the organisation through the behaviour features (*BehaviourFeature*) an agent may have to play role. Then, to play a role, an agent may have the capabilities which allow him to carry out the behaviour features (*BehaviourFeature*) of the role. The agents have an organisation behaviour (*OrganisationBehaviour*) which allows (1) to play and to leave roles in organisation and (2) to know the members of the organisation. OrganisationBeahaviour is an abstract behaviour and depends on the domain.

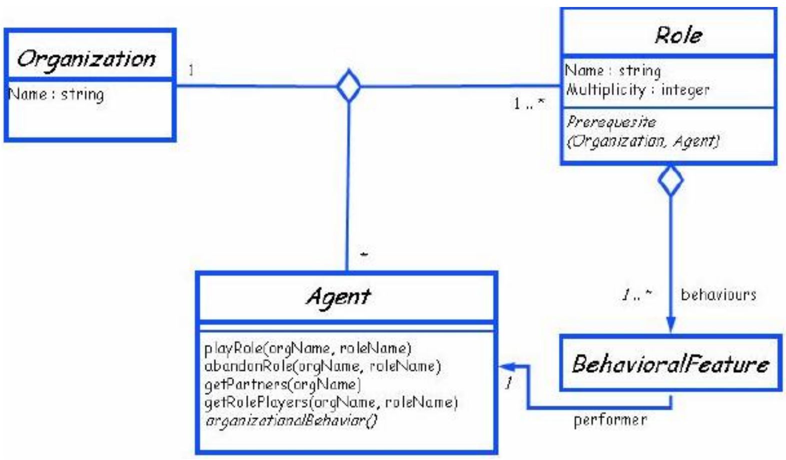

Figure 3.12: MASCARET generic organisational model

Groups and roles in MASCARET are represented as first class entities. The agents can enter and leave dynamically groups and roles. In addition MASCARET allows groups creation and deletion in run-time. MASCARET takes into account several types of organisation: physical organisation, social organisation, mediation organisation and human organisation. The physical organisation describes the physical activities of entities compounding the environment. Then the environment is represented through an organisation and does not exist as an entity. In addition, as AGRE, the agents cannot perceive the physical environment through their social roles.

3.9.10 The ISLANDER model

ISLANDER (Esteva et al., 2001) provides a framework for the specification of the *electronic institutions*. The authors assume that human institutions not only structure human interactions but also enforce individual and social behaviour by obliging everybody to act according to the norms. Basing on this assumption, they proposed a framework using the notion of *scene*, *role*, *illocution*, *performative structure* and *norms*.

The agents in ISLANDER interact through their roles in the context of *scene*. A *scene* specifies an activity in term of interaction pattern between roles. At each *scene* a set of illocutions are associated. An illocution comprises a type of message, a sender, a receiver and the content of the message. Agents can enter and leave dynamically the scenes and they can enter simultaneously in several *scenes*. In addition, agents can move from a scene to others *scenes*. The agents moving from a scene to another scene are constrained by the rules defining the relationships among scenes. These relations are defined by the *performative structure*. It defines what agents depending on their roles can move from a *scene* to other *scene*. It allows to specify a network of scenes and more complex activities. The interactions between agents are regulated through a set of norms. The norms define commitments, obligations and rights of agents.

3.9.11 The OMNI model

Organizational Model for Normative Institutions (OMNI) model (Dignum et al., 2004) is a unification of Opera (Dignum, 2004) and the Harmon*IA* (**?**). OMNI is an integrated framework for modelling a whole range of MAS, from closed systems with fixed participants and interaction protocols, to open, flexible systems that allow and adapt to the participation of heterogeneous agents with different agendas. The OMNI framework is composed of three dimensions existing at three abstraction levels:(Fig.3.13):

1. the Normative Dimension of the organization, which specifies the mechanisms of social order, in terms of common norms and rules that members are expected to adhere to.
2. the Organizational Dimension of the organization, which describes the structure of an organization, and can therefore be viewed as a means to manage complex dynamics in societies.
3. the Ontological Dimension, which defines environment and contextual relations and communication aspects in organizations.

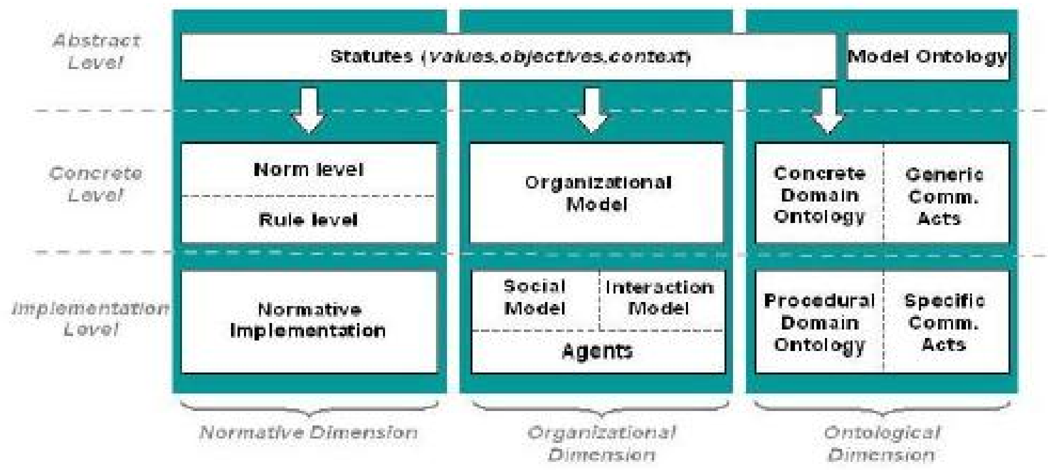

Figure 3.13: Levels and dimensions in the Omni framework

The separation of the organisation structure, the interactions structure and the normative structure from the agent allows ensure consistency in MAS building and a coherent behaviour of the system. Unlike most models, OMNI provides capabilities for agent interpretation of society objectives, norms and plans. It makes difference between the organisation behaviour and the agent behaviour. A role in OMNI can be viewed as an observable behaviour of an agent for other agents. Then, the specification of MAS structure with OMNI ensures the autonomy of the agents.

3.9.12 Discussion

3.9.12.1 Relation between role architecture and agent architecture

The first principle of OCMAS introduces a distinction between the "how" and the "what". It means that the role describes the expected behaviour of an agent within an organisation and not the how it is achieved as long as the function of the role is conserved. Therefore, the question is how the actual performance of the role is related to the role specification. Gaia (Wooldrigde et al., 2000) defines a role as an abstract description of the agents' function. The notion of role appears only at the analysis/specification stage. At the design stage, the notion of role disappears. The AGR (Ferber and Gutknecht, 1998) methodology defines a role as an abstract function of an agent in a group. Accordingly no assumption is made on the agent architecture as long as the function is fulfilled. Actually, in the AGR implementation: MadKit, the roles are just represented as labels and nothing is done to enforce any role specification. In Hilaire's model

(Hilaire et al., 2000), a role is also defined as a function which is common to a set of agents. A role is defined as a class in the Object-Z formalism and can be inherited to specify specific roles. The Hilaire's model increases modularity and reuse of the roles. But the roles completely define the mental properties of the agents and the behaviour related to the role. An agent is defined as a collection of roles, hindering the possibility to acquire or leave a role at run-time. MOCA (Amiguet et al., 2003) is an extension of Hilaire's proposition with the possibility to dynamically create groups, to endorse roles or to leave them. As in (Hilaire et al., 2000), a role in MOCA encompasses both the properties and the behaviour to be performed in order to fulfill the role. However, the agent architecture is more complicated and considers the role as components which can be created or destroyed dynamically when the agent is entering or leaving a group. In both these approaches, there is a one-to-one correspondence between the "what" and the "how", i.e. each role is achieved by one and only one way by an agent component. Therefore there is no reason to distinguish "what" and "how" as is explained in (Amiguet et al., 2003) where the role is considered as a component which is both external toward the group and internal toward the agent.

In OREA, we want to take the separation of concerns between the "what" and the "how" seriously by distinguishing between (1) the decomposition of an organisation into functional roles from an external and global point of view, and (2) the decomposition of an agent into aspects (see later) from a local and internal point of view. In effect, there is no reason to assume that the decomposition of the behaviour of an agent corresponds to the decomposition of its behaviour in terms of its expected outcomes within an organisation. Unlike MOCA, we assume that the role does not implement how it is played (Table 3.1). The role playing specification is defined through the aspects. Then, one can specify through aspects how a same type of role is played differently by different types of entities.

Table 3.1: Comparing MOCA role and OREA role

MOCA role	**OREA role**
Defined as component	Defined as specification
Has its own dynamic	Its dynamic is controlled by the aspects
Internal and external	External

We use a component-based approach as in MOCA to define the architecture and behaviours of entities. The architecture of an entity is a set of components interacting to achieve tasks in local point of view. For that, the notion of *aspect* is used. An *aspect* describe the agents mental properties and how the agents behave according to the internal and external contexts. Then, while the roles describe the external properties, the aspects describe the internal properties.

In Casssiopea, the entities behaviours are specified only through the elementary behaviours. In OREA the entities behaviour is specified through the notions of aspects and competences. In addition, the local dependencies do not concern the elementary behaviours (competences) but the aspects which are the sub-division of an entity dynamics. The dependencies between the aspects are defined through the notion of influences. As Cassiopeia, the organisational behaviours can be separated from the behaviours relevant to the domain. To do that, we use a special aspect (*InteractionAspect*) to manage groups formation and dissolution.

3.9.12.2 Roles and norms

An organization constrains the agents behaviours and structures their interactions. In most OCMAS models (Dignum et al., 2004, Esteva et al., 2001), the constraints are explicitly defined as set of collective and individual norms. The norms define the obligations, authorizations, conventions which govern the agents activities. The roles playing constraints are defined using the norms. When an agent enters a role, it acts within the organization/institution according to the role constraints. The norms specify "how" agents may play roles and interact among them. In our proposition, we do not use the notion of norms to constraint the behaviours of the entities within organization. The interactions between entities are structured as a set of protocols between roles that the entities have to follow.

3.9.12.3 Roles, agents and competences/capabilities

In a component-based approach (being roles, competences or elementary behaviours), playing a role depends in part on the capabilities of the agents to provide some services and resources. Therefore the notion of competence has been introduced very early in the OCMAS approaches from AGR to MOCA. A competence or capability is the abstraction of a service which is needed or provided by an agent and more particularly by a component. Again we distinguish three kinds of contributions depending on the approach used to take into account agents and roles capabilities. The first kind (Wooldrigde et al., 2000, Ferber and Gutknecht, 1998, Querrec, 2002) defines all the capabilities inside the agents architecture. In these models, the roles use the agents capabilities to define their dynamics. The second kind (Hilaire et al., 2000, Hübner et al., 2002) defines the capabilities in roles architecture. The agents do not provide any capabilities in these models but by having or by acquiring roles. The third kind (Amiguet et al., 2003) assumes that the agents as well as the roles can provide capabilities. The two first kinds are easy to implement but they are not realistic. A role defines the function of agent in an organisation. Then, a role may provide some capabilities to agents to carry out some services linked to this function. But, an agent can also provide some capabilities independently from the roles it plays, that it is necessary to specify independently from the roles capabilities. MOCA takes into account this distinction. The behaviour of roles depends in part on agents capabilities. A role in MOCA is both internal and external. In addition, it is impossible to play the same role in different ways. For example, in the carbon cycle, soil, plants and the atmosphere play the role of storage. But they do not store the same elements and do not have the same dynamic. Thus, the function of storage is not necessarily the same for the plant, soil or atmosphere. A role as defined in most OCMAS models, does not take into account this specification.

In our proposition, we assume that (1) a type of role can be played in different ways and (2) the roles and the agents provide capabilities (competences), while the aspects may need competences to behave. Each entity controls its own capabilities and aspects, and the roles define only the external features. This specification has some consequences in the way the roles can be acquired and played:

1. The verification for roles acquisition does not depend on agents capabilities. The verification depends only on the global structure of the system: types of agent, types of role, cardinalities, etc.
2. An agent may have its own behaviour which allows him to carry out its competences according to the contexts.

3.9.12.4 Environment

Several propositions intended to deal with environment integration with organisation. (Parunak and Odell, 2002) represents the environment as a social component in an organisation. But the environment does not play any role within groups. Their proposition is only a methodology and guideline for OCMAS representation with UML and AUML notions. In AGRE (Ferber et al., 2005) provides a flexible framework to integrate environment with organisation. The authors make a clear distinction between the social structure and the physical structure. The physical and social spaces are represented by areas.. AGRE allows representing explicitly environment and defining adequately the physical constraints. However, the objects cannot be individuated explicitly in their interactions with the agents. MASCARET (Buche et al., 2004) represents the environment as an organisation in order to describe the physical activities of the objects compounding the environment. Then, to take place in an environment an agent may play roles in the physical organisation. But as in AGRE, no organisation being able to rely on both objects and agents can be described.

But the perception of an agent on its environment can depend on its interest and therefore an object may have different roles depending on the object-agent interactions it is embedded in. For example, in an agrosystem, a farmer perceives a piece of land as a site of production while the administration perceives it as tax raising entity. For the breeder, the same piece of land can represent a pastoral site. To take into account the perception of actors on their environment according to their point of view, we propose to represent the environment objects as playing roles within the organisation structure.

In our proposition, the environment objects are represented as entities playing roles in groups. Other agents can perceive the environment and interact with it through their roles. Then, as in AGRE it is possible to represent simultaneously several environments in which the agents act to meet their objectives.

3.10 Conclusion

This chapter allowed defining the background of our study. This chapter provided a full description of some OCMAS. In this chapter we showed how the OCMAS models deal with macro and micro levels description. Gaia model proposes a meta-model describing a MAS both at the macro and micro levels. But the macro level is not explicitly represented. In addition, the fact the roles are transformed into agents at the design stage makes Gaia an ACMAS model more than an OCMAS model. Based on the concepts of agent, group and role, AGR allows an explicit description of the macro-level and micro levels. But, the implementation of AGR in Madkit does not provide an explicit separation between the macro and micro levels.

However, the extensions of AGR such as Hilaire's proposition, Parunak and Odell proposition and MOCA proposed frameworks to deal with an explicit description of the notion of group and role. The role is defined are recurrent pattern of interactions and behaviour in organisation. These extensions provide more concepts than AGR to make easer the description of MAS. Based on the reification of the notion of group and roles, Hilaire's proposition and MOCA increase the reuse and modularity in organisation description. Additionally, the use of component-based approach by MOCA allows to define the agents with evolutive behaviour. But these models as AGR fail to separate explicitly the macro and micro levels. Roles in Hilaire's proposition and MOCA define both the status and the behaviour of the agents. Then, the roles are both internal and external. To increase the genericity, the reuse of the organisation structure, it is necessary to do not take into account the micro-level in the description of the macro-level. In these models, a same type of role cannot be played in different ways. Another limitation of Hilaire's proposition and MOCA is that the environment is not taken into account. Parunak and Odell proposition, AGRE,and Mascaret attempt to integrate environment with organisation but they fail to take into account the perception of the agents depending on their roles.

In the next chapter, we present the OREA model, the first part of our contribution: the OREA model. OREA deals with explicit description and separation of macro and micro, the environment description in organisation and how a same role can be played differently.

Part II

The OREA model

Chapter 4

The OREA model

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4.1 Introduction

Modelling complex systems (CS) that cover multiple domains, for their better understanding, increasingly demands collaboration between different disciplines. However, these disciplines do not necessarily share the same points of view on the real objects of the system, and these points of views can be complementary. In addition, the representation of such systems requires multi-scale description implying at least the micro-level, macro-level and underlying environment. Our objective is to propose a framework which allows multi-points of view description as well as at the macro-level than the micro-level. Basing on the OCMAS approach, the OREA model has been proposed.

In the Chapter 3, we have showed that the OCMAS models allow dealing with macro and micro levels description. But these models are interested in the MAS modelling and implementation rather than the CS modelling. In addition, these models fail to take into account a clear separation between the macro and the micro levels. Sometimes, the macro-level is implemented at the micro-level as in AGR. Sometimes, the micro-level is defined at the macro-level as Hilaire's proposition and MOCA. The organizational structure of these models lacks of genericity and does not provide more flexibility. As another limitation, these models do not take into account the perception of the agents according to the roles they play in the system. The environment plays an important role in CS. The environment supports objects such as resources. The objects are in relation among them and with the agents. However, they have not necessarily the same nature of relations among them. They provide services and their behaviour is necessarily dependent of different interactions. For example, a plant does not interact in the same way with the soil than with the animals. The nature of relations between plant and soil is different from the nature of relation between plant and animals. The soil is a provider of resources to plant which is a resource for the animals. The representation of the environment requires integrating an explicit definition of the nature of relations and interactions among objects and agents independently from their description. For that, the environment objects must be represented in the organisation structure and play roles as agents. This specification allows defining the perception laws on the environment through the roles the agents play.

The OREA model definition is based on the extensions of the AGR model. We use the following assumptions to define our framework:

- the macro-level must be defined independently from the micro-level i.e. the macro-level does not know the nature of the micro-level.
- an organisation represents a point of view on a system at the global level.
- the objects (resources, objects, agents) embedded in the system are represented through the notion of *entity*.
- the internal and external features of the entities must be explicitly and separately defined in order to ensure the coherency of a model.
- the environment objects must be explicitly defined in the organisation structure in order to

specify the perception laws by taking into account the nature of relations between entities and not the nature of entities.

This chapter is organized as following: the first part presents the OREA meta-model and dynamics, the second part describes the implementation of the OREA meta-model and the third part concerns the OREA methodology.

4.2 The OREA meta-model

The OREA meta-model provides two levels of description: the *Abstract level* and the *Concrete level*. The *Abstract level* provides the description of a model structure. The *Concrete level* describes a model as an instance of the abstract level. At each level of description, the OREA concepts can be divided into two categories according to the points of view on the entities: the concepts of macro-level or the system-level which describe the external features and the concepts of the micro-level or component-level which describe the internal features of the entities.

4.2.1 The abstract level

The abstract level provides the concepts for the description of the structure of a system at macro-level (from an external point of view) and micro-level (from an internal point of view) (Fig. 4.1).

4.2.1.1 The macro-level

The macro-level is interested in the description of the organisational structure of a system. It is based on the concepts of organisation and role type which define the structural description and the concepts of Competence type, influence type and Protocol description which specify the behavioural aspect at the macro-level.

organisation

An organisation provides an abstract description of a group. It is defined by a set of role types, the cardinalities of role types and their relationships. The cardinalities of a role types within an organisation define the minimum and maximum players of the role type. The relationships between roles define the structure of group and the relationships between the entity types. It addition to the role descriptions and their relationships, the organisation provides the description of the interactions between role types through the notion of protocol description. As

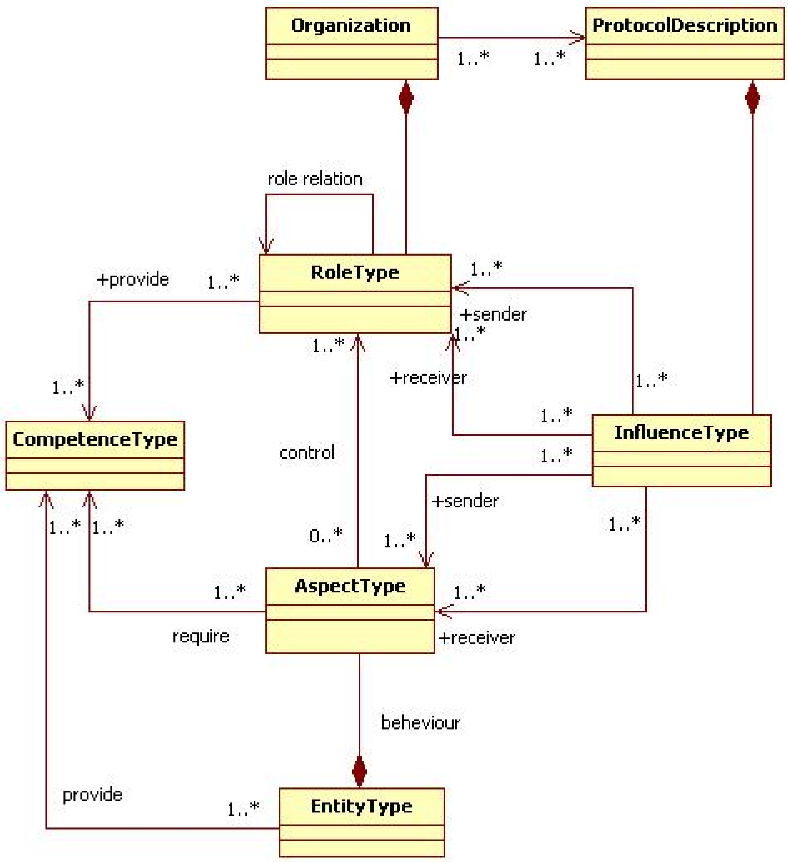

Figure 4.1: The OREA metamodel abstract level

an example of organisation, in the C dynamics modelling context at village scale, the Production is an organisation describing the plant and animal production. An organisation is described as following:

$$organisation = \langle name, \{RoleType\}, \{ProtocolDescription\}\rangle$$

Role Type

A role type is an abstraction of an entity function, an external point of view on a type of entity. It describes the external features i.e the observable behaviour of an entity type. From the behavioural point of view, the role description is interested only in the expected interactions in which the roles evolve. This description is provided by the protocol descriptions. In addition, a role type is characterized by a set of competences types that it type provides. As an example of role type, the *Producer* describes a role in the *Production* organisation.

Competence Type

At each role type, some responsibilities are associated. These responsibilities are defined by the competence types. A competence type provides an abstract description of an elementary behaviour of a Role Type and an Entity Type. It defines the capability of an role type or entity type to achieve some services. The notion of competence type increases the modularity and the independence of the organisational structure. It makes possible the use of the role competences without interesting in the organisational structure. In addition, the notion of competence allow entities to reason about the behaviour of other entities and interact in coherent way. In other terms, the notion of competence ensure the coherency of a system. For example, the "CultivationSkill" describes the capability to drive crop cropping.

Protocol description

The entities in a CS are not isolated. They interact among them at different scales of time and space. Their interactions are recurrent and require an explicit description. The interactions occur in organisational context. Then:, the interaction descriptions must be interested in the interactions between role types and not to the nature of entities. That allows to define the organisational behaviour without interesting in the nature of entities and an explicit separation between the macro and the micro levels. The description of interactions is provided by the notion of protocol description. It is defined as a set of exchanged messages between role types. The exchanged messages are defined using the notion of influence type

The influence type is an abstract description of an influence (Ferber and Müller, 1996). Ferber and Müller (1996) use the notion of influence in order to do an explicit separation between the actions of agents and the consequences of these actions on the environment. Then, an action is divided into two phases: the influences production by the agents' behaviour and the reaction of the environment. The Protocol description is defined as following:

$$Protocoldescription = \langle name, \{\langle InfluenceType, source \in RoleTypes, destination \in RoleTypes\rangle\}\rangle$$

The macro-level in OREA is defined without doing assumption on the micro-level. In other words, the macro-level is not interested in the *individuals nature*. The behaviour description at the macro-level concerns only the protocol descriptions which constrain the entities behaviour within the organisation. In Hilaire's proposition and MOCA, the macro-level description includes both the description of the interactions and the roles behaviour. In others terms, the macro-level describes both how the individual behave within organisation and from the local point of view. In OREA, we assume that the way in which entities behave and reason about the social organisation is expressed at the micro-level.

4.2.1.2 The micro-level

The macro-level allowed to define the organisational structure which provides framework to constrain the entities behaviour from local and global point of view. The micro-level is interested in the specification of the entities behaviour from the local point of view i.e. how they reason, make decision and react to the external perturbations. The local behaviour of the entities is specified using the concepts of entity type, aspect type and competence.

Entity type

In OREA, the individuals (e.g. humans) object and resources (e.g. plants, herbaceous) are described by the notion of Entity Type. The entity type provides an abstract description of a category of entities (passive or active objects) which have the same structure. Externally an entity type is described through the role types and internally through aspect types. The aspect types of an entity type corresponds to the decomposition of its internal structure . The structure of an entity is characterized by the types of provided competences, the aspect types. The structure of entity type is defined as a set of properties, possible states (S) and aspect types:

$$EntityType = \left\langle P, S, 2^{CompetenceType}, 2^{AspectType} \right\rangle$$

where P defines the attributs of the entity type as following:

$$P = \{\langle name, type \rangle\}$$

In the C dynamics modelling context, the *Family* is an entity type. It provides the abstract description of the households. The internal properties of *Family* are defined through a set of aspect types.

Aspect Type:

As noticed previously, role description is interested only in the expected interactions. In addition, the roles descriptions do not include how they are played. In OREA, the roles playing is specified through the aspect types. An aspect type describes the internal behaviour of an entity type and how the roles type are played internally by an entity type. The description of the behaviour of an aspect type is based on the competence types provided by the role types and entity type. An aspect type controls several role types. An aspect type controls a role type if it defines how this role type is played. The relationship between an entity type and an aspect type is a one-to-one relationship. But an entity type can have several aspect types. Two aspect types of a same entity type can control a same role type but they do not share the same attributes of the entity type. Then, the aspect types do not depend only on the role types they control but also on other aspect types of the same entity type. Each aspect type provide two interfaces which describe its dependencies with other aspect types and role types: *InternalInterface* and *ExternalInterface* (Fig. 4.2). The *InternalInterface* describes the dependencies of an aspect type with other aspect types and the *ExternalInterface* describes the dependencies with the role types. In other terms the interfaces describe the interactions link between aspect types in one hand and between aspect types and role types in other hand. The aspect types dependencies are defined using the notion of influence type. An aspect type is defined as following:

$$AspectType = \left\langle P, S, 2^{CompetenceType}, 2^{RoleType}, InternalInterface, ExternalInterface \right\rangle$$

where the *ExternalInterface* and the *InternalInterface* are defined respectively as follow:

$$ExternalInterface = \{\langle InfluenceType, role \in RoleTypes \rangle\}$$

$$InternalInterface = \{\langle InfluenceType, aspect \in AspectTypes \rangle\}$$

The *PlanningAspect* is an example of aspect type. It describes a part of the *Family* entity type dynamics and features. It controls the *Producer* role type. The *PlanningAspect* describes how the *Family* entity type plans production and plays the *Producer* role type.

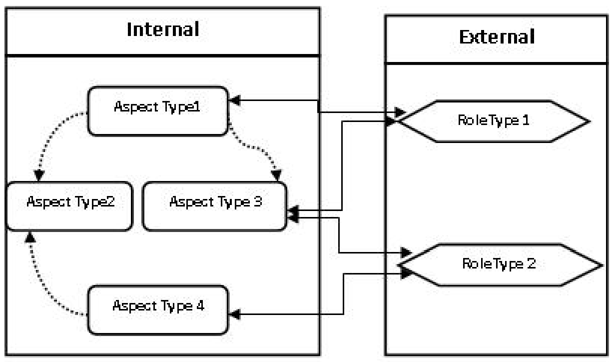

Figure 4.2: Dependencies between Aspects and roles

By specifying in aspects the local behaviour of the entities and how they play roles, OREA allows different entity types to specify differently how the same role will be played. In most models, the roles descriptions include their behaviour. This specification does not allow to take into account the concerns related to each entity type. In these models, to take into account the concerns related to each type, the modeller must define a new role type by inheritance. In OREA, these concerns are specified in the aspects. Then, OREA increases reuse and evolution of organisation structure. It is possible to introduce in the system new entity type which new concerns without modifying the organisational structure.

Additionally, OREA makes possible an explicit separation between the organisational behaviour of entities and their local behaviour. The roles which define the organisational behaviour represent the observable behaviour from the external point of view. They allow entities to be in relation and interact between them. The local behaviour defined by the aspects represent the entities activities and how they reason about the social organisation. The separation between the organisation behaviour and the local behaviour of entities can be viewed as a separation between the *mind* and the *body* of the entities (Michel, 2004, Soulié, 2001, Magnin, 1996).

The *mind* concerns the internal structure of the entities. As to the *body*, it defines the manifestation of the entity in the environment. While the *mind* description is provided by the entity, the *body* description is provided by the environment. The separation between the *mind* and the *body* allows a modular implementation of a system and preserves the integrity of the system both at the micro and macro levels. In OREA, the *mind* is defined by the aspects and the *body* is defined by the roles. In comparison to the Soulié's proposition Soulié (2001) the aspects implement the autonomy and the representation of the environment while the roles define the perception and the action on the environment. As in Soulié's proposition , the two parts are inter-dependent and influence each other. We use the notion of influence to define the relations between them.

4.2.2 Concrete level

The concrete level is an instance of the abstract level. It defines the state of a system at a given moment. The concrete level is based on the concepts of groups and roles at the macro-level and entities and aspects at micro-level (Fig. 4.4).

4.2.2.1 The macro-level

Group

At the concrete level, a system can be viewed as a set of groups interacting through entities playing roles in these groups. Each group represents an instance of an organisation. The groups

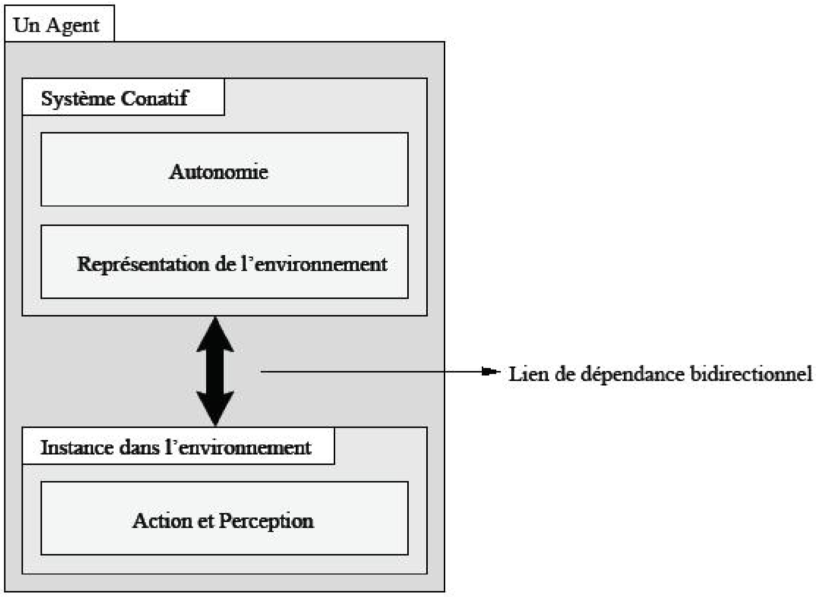

Figure 4.3: The external and internal parts of agent in the Soulié proposition

define the framework in which the entities exist and interact among them through their roles. In other terms, a group is a set of roles in interaction.

Role

A role is an instance of a role type. It defines the membership and the interface of an entity within a group. A role is in relation with others roles with which it interacts within a group. Then, a role allows to an entity (player) to be in relation and interact with other entities in the group. However, a role is closed to a group. Only the roles of the same group can interact between them. The interactions between roles are driven by a set of protocols.

Protocol

A role can take place simultaneously in several interaction processes. It is necessary for the roles, to know exactly the situation of each interaction process for a coherent behaviour. Then, for each interaction process the roles use a protocol that they share between them. A protocol is an instance of a protocol description and is defined as set of influences exchanged. The state of protocol determine the situation in an interaction process. It is defined as follow:

$$Protocol = \langle name\,\{\langle influence \in Influences, source \in Roles, destination \in Roles\rangle\}\rangle$$

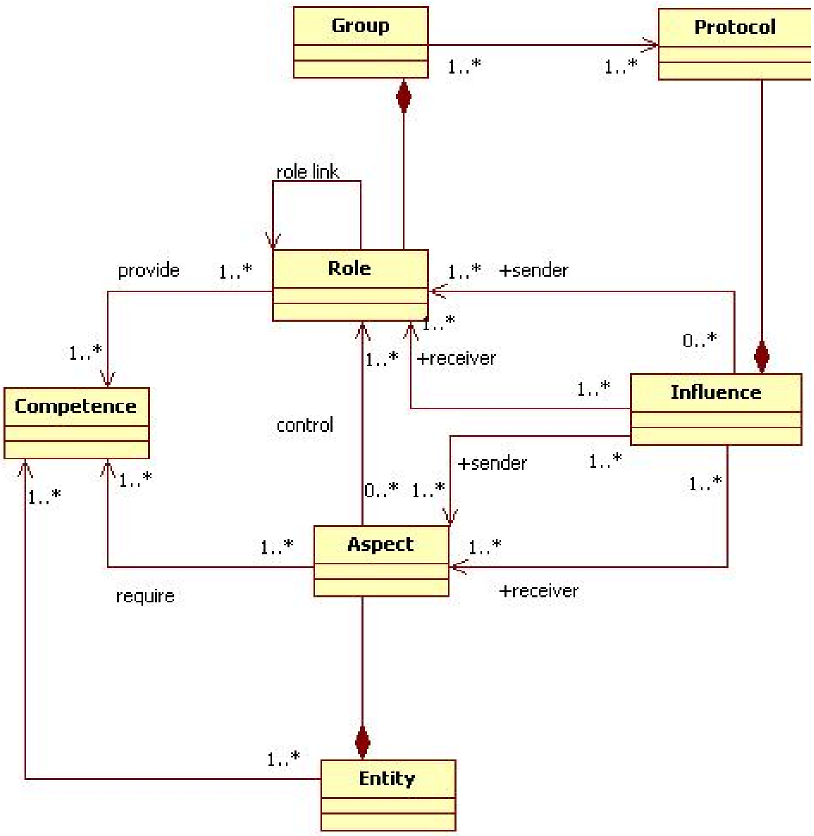

Figure 4.4: The OREA metamodel concrete level

An influence is an instance of an influence type. An influence may be physical or a basic message. It is used by the roles for their interactions.

Competence

A competence represents an instance of a Competence Type. A competence is provided by a role or an entity. A competence can be viewed an object providing some methods which can be executed to achieved some tasks.

4.2.2.2 The micro-level

Entity

An entity is an active or a passive object in the system. The behaviour of an entity arises from the aspects and the roles dynamics (Fig. 4.2). From the internal point of view, the entity behaviour is based on the aspects in interaction. From the external point of view, the entity behaviour is based on the roles. An entity can play simultaneously several roles in several groups.

In addition, an entity can play simultaneously the same role type but in different group. The separation between the internal from the external behaviour of the entity provides a flexible way to define the entity behaviour. An entity in OREA is defined through its description provided by the Entity Type, its initial state (s_0) and the set of aspects defining its dynamics.

$$Entity = \langle EntityType, s_0 \in EntityType.S, \{Aspect\} \rangle$$

Aspect

Suppose an entity playing simultaneously the *seller* and *buyer* roles. It is clear that the buying power of the entity depends on what it sells. This dependency is internal and requires the integration of a mechanism in the entity structure which allows ensuring the coherence of the entity's behaviour. The aspects are used in this case. The aspects manage the entity process decision in buying and selling activities. In other terms, the aspects implement the decision model of the entity. Then, while the roles allow the entity to interact, the aspects allow entity to react to the external events and make decision. In addition, the aspects implement when and in what context the entity plays roles. The roles and aspects are complementary for a coherent behaviour of an entity (Table 4.1). The dynamics of an aspect is based on the competences of the entity which handles it and those provided by the controlled roles. An aspect is defined by its aspect type and its initial state:

$$Aspect = \langle AspectType, s_0 \in AspectType.S, roles \in AspectType.RoleTypes \rangle$$

Table 4.1: Complementarities between aspect and role

Role	Aspect
Describes what	Describes how
Provides competences	Requires competence
Extrinsic features	Intrinsic features
External behaviour	Internal dynamics

4.2.3 Relation between macro and micro levels

The OREA meta-model includes both the micro and macro levels. The micro and the macro levels are defined explicitly and separately. Concretely, the two levels coexist and influence each other. The entities are embedded in the macro-level through the roles they play. The macro-level has no control on the entities decision model and their state. In other terms, the micro-level is not accessible by the macro level and inversely (cf. section 4.3 page 66). The entities control their own behaviour and state through their aspects. However, the macro-level provides behaviour features for the entities internal behaviour through their roles and define the entities interactions. The relationships between macro and micro levels are expressed through the aspects and roles using the notion of the influence (aspects interfaces description). The aspects constitute the input and the output ports of the entities allowing them to interact with the macro-level (cf. section 4.3).

4.3 Dynamics

4.3.1 The organizational dynamics

As in most role-based models, OREA allows the groups formation and disbandment in run-time. The entities can enter and leave dynamically roles. If an entity plays a role, it acquires all competences of this role. The entities create groups according to their objectives. If all members leave a group, this last is automatically destroyed from the *system*.

The groups know the organisation they instantiate and manages the roles playing. When, an entity requires a role in a group, the group verifies if the entity can play the required role according to the description of the group structure (organisation).

In OREA, it is possible to create simultaneously several groups of the same type. Two entities can interact if only if they belong to a same group. Always, the entities interact through their roles.

4.3.2 The dynamics of the entities

An entity has its own dynamics which allows it to achieve tasks and to react to the external events. Its behaviour is divided into external and internal dynamics (Fig.4.5).

The roles playing depend on the aspects handled by an entity. If an entity handles an aspect, it may play all roles required by this last because the aspect uses the competences of roles for its behaviour. If an entity handles an aspect, this last can be executed only if all required roles are handled by the entity. An entity can leave dynamically its aspects in run-time. For example, if an entity leaves all roles required by an aspect, it leaves also this aspect because this last cannot be executed.

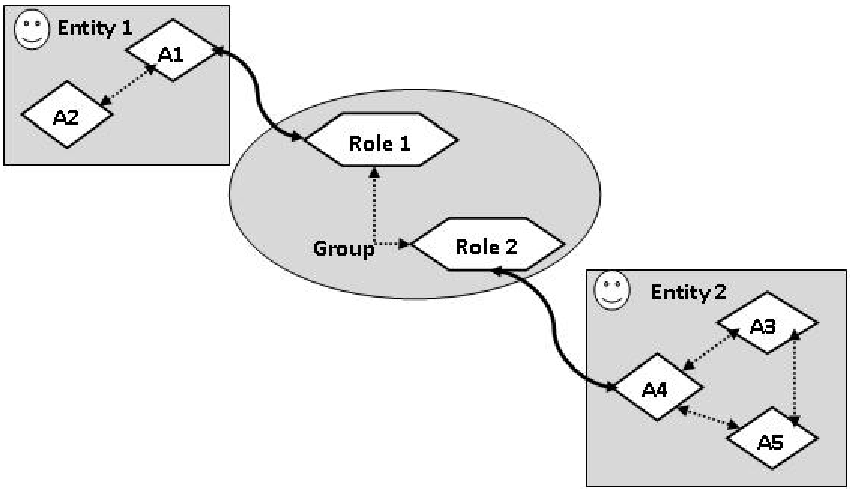

Figure 4.5: Entities behaviours from the internal and external points of view

4.3.2.1 The external dynamics

The roles have been defined as autonomous components and they are external to the entity structure. The roles interact not only with other roles but also with the entities which play them. The interactions of roles arise from the local behaviour of the entities which receive the result of the perception and interactions through the roles.

A role in OREA presents two interfaces of communication (Fig. 4.6). The first interface allows role to communicate with entity: the *Internal interface*. The second allows communication with other roles: *external interface*. As to entity, it has one interface to interact with its roles. Then, an influence sending in OREA is divided into three steps (Fig. 4.7). The first step concerns the influence sending by the entity initiator to its role (role sender). At the second step, the role sender sends the influence to the role(s) destination. At the third step, the destination role sends the influence to its player. This last reacts to the received influences by executing its aspects.

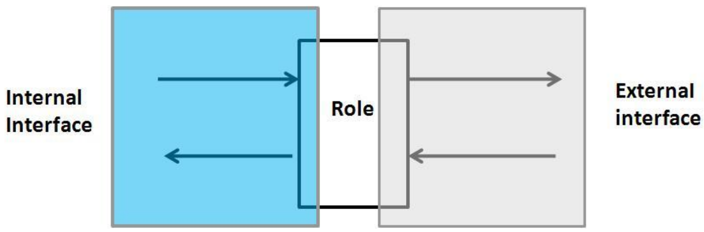

Figure 4.6: Interfaces of role

Three strategies are used by the entities for sending influences :

Sending influence to all members of a group: the role sender gets from the group all role members and sends the influence to each role. Then, all entities playing roles of the group

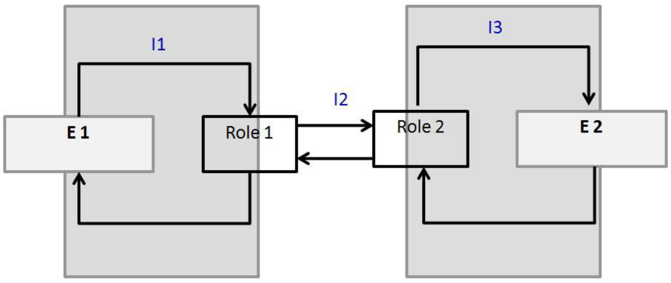

Figure 4.7: Interaction between two entities E1 and E2

will receive the influence.

Sending influence to entities playing a role type: the role sender gets from the group all concerned roles and sends the influence.

Sending influence to a specific role: this case occurs when an entity may respond to an influence. All received influence contains the identity of the role initiator. Then, the response to the influence is sent directly to this last by an entity role.

4.3.2.2 The internal dynamics

Unlike roles, the aspects are internal to the entity structure. The aspects of an entity are executed according to the objectives of the entity or to the external events. As noticed previously the entities interact between them in order to require services. The entities ability to provide some services depends on their aspects which depend on competences. If an entity receives an influence, some aspects are executed in order to provide the required services. The entity uses a mechanism of selection to determine what aspects to execute. This mechanism uses the description of the influences and the aspects interface to do the selection. Then the selected aspects are executed.

From the local point of view, the aspects can interact between them to share data or to require some services. Then, an aspect has some autonomy, it controls its own dynamics and state. In addition, two aspects cannot control the same entity's attributes. This specification increases the cohesion of entity behaviour.

4.4 The implementation of OREA

The implementation of the OREA meta-model is based on the reification of the different concepts. Two components handle the abstract and the concrete level: the `ModelDescription` and the `Model` components.

The `ModelDescription` provides the description of the abstract level. It can be viewed as an ontology of domain describing a system structure. The `ModelDescription` allows the entities to have the same meaning, the same description of the elements they share between them. The `Model` describes the concrete level. It manages the system dynamics (group formation, roles playing, etc.). It behaves as an autonomous entity interacting with the other entities. All entities are linked to `Model` component. Then, to handle a role or to create a group, the entities interact with `Model` component. The interactions of the entity for roles handling are managed by a specific aspect (`InteractionAspect`) (cf. section 4.4.3 page 73). Then, if an entity requires a role, it sends an influence to `Model` (Fig.4.8). This last according to the description of the required role (organisation and role type), it creates an instance of the role and links the role to the entity (cf. section 4.4.2). After the role creation and initialisation, the role informs its player by sending an influence.

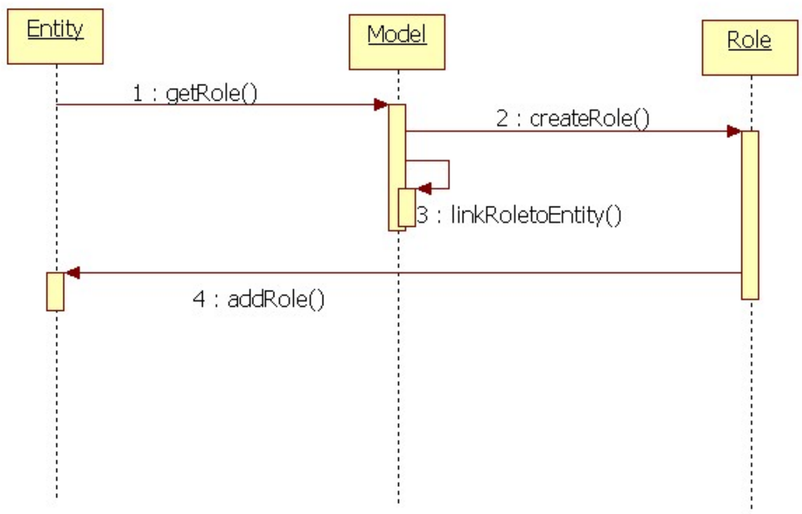

Figure 4.8: Interactions between an entity and the Model component for the role playing

The relations between the different elements have been reified at the abstract level and at the concrete level. At the abstract level, we use the notion of *relationship* to relate the elements; at the concrete level, we use the notion of *link*.

4.4.1 The relationships

A set of abstractions have been proposed (Table 4.2) to define explicitly how the elements are related among them. The relationships abstractions provide a framework for a better description and verification of a system structure. In OREA, the relationships are not bidirectional. For example, a RoleType does not know the AspectTypes controlling it.

4.4.1.1 The Ownership relationship

The *Ownership* relationship describes the membership of a role type within an organisation i.e. the relationship between a role type and an organisation. It is characterized by the organisation, the role type and a cardinality. The cardinality defines the minimum and maximum players of a role type. The *Ownership* relationship is defined as follow:

$$OwnerShip = \langle Organisation, RoleType, Cardinality\rangle$$

4.4.1.2 The PlayRole relationship

PlayRole relationship is an abstract description of role playing relation between an entity type and a role type. It defines the number of an entity type instances which can play a role type. It is defined as follow:

$$PlayRole = \langle EntityType, RoleType, Cardinality, dependencies \in RoleTypes\rangle$$

4.4.1.3 The RoleRelation relationship

The *RoleRelation* describes the relationship between two role types within an organisation (Fig.4.9). The *RoleRelation* relationship defines the organisation structure. It is defined as follow:

$$RoleRelation = \langle Source \in RoleType, destination \in RoleType, Cardinality\rangle$$

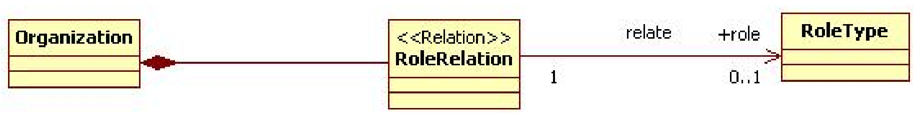

Figure 4.9: UML representation of role relationships

4.4.1.4 The Behaviour relationship

The *Behaviour* relationship defines the internal structure of an entity type. It describes the relationships between an entity type and an aspect type (Fig. 4.10). It is characterized by the entity type and the aspect type it relates.

Figure 4.10: UML representation of Behaviour relationship

4.4.1.5 The Dependency relationship

The *Dependency* define the interaction links between components of an entity. The *Dependency* relates AspectType and RoleType through the notion of influence (Fig.4.11). This description allows defining how entities react to the internal and external events.

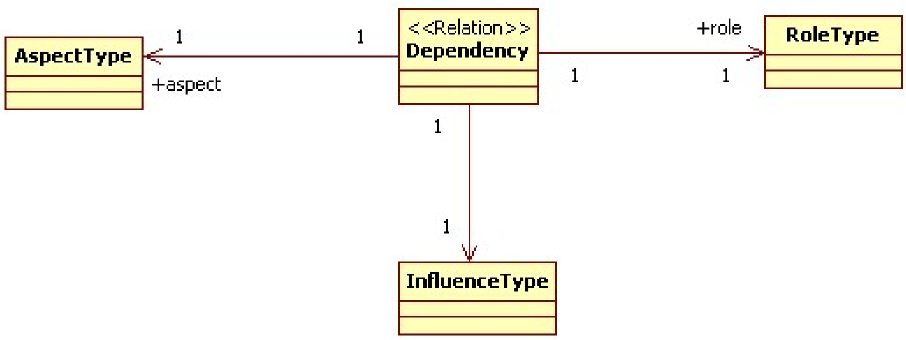

Figure 4.11: UML representation of Dependency relationship

Table 4.2: The types of relationship in OREA

	Organisation	*RoleType*	*EntityType*	*AspectType*
Organisation			OwnerShip	
RoleType		RoleRelation		
EntityType		PlayRole		Behaviour
AspectType		Dependency		Dependency

4.4.2 The structure of the components

The OREA meta-model implementation is based on the DEVS formalism (Zeigler et al., 1996) and MIMOSA (Fig.4.12). The DEVS formalism allows defining how an entity reacts simultaneously to the internal and external events. In addition, the DEVS formalism is a relevant way to separate the action production from its consequences as defined by the *reaction-influence* model.

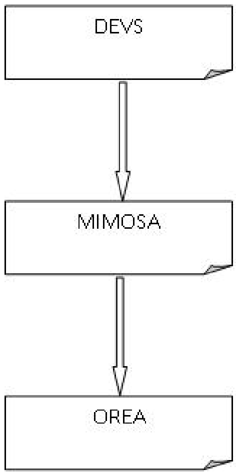

Figure 4.12: The implementation of OREA model

At the concrete level, the groups, roles, entities and aspects are defined as DEVS components. Each component has its own control and interact other components.

In DEVS, a model is a set of models or atomic components with inputs and outputs ports and linked by these. A port is characterized by its name and its index. The index allows defining a specific component if a component is linked to many components through a same port. In MIMOSA, the components interact between them through ports. We use the ports not only to link the elements at the concrete level of OREA but also for their interactions. A *port* is a concrete implementation of the *link*.

A role is linked to a group through the "owner" port (Table. 4.3). A group is linked to all roles through the "members" port. The "members" port links a group to all roles in the group. The group uses this port to send the broadcast influences to its members . In addition, for each role type a specific port is defined linking the group to the instances of the role type. This port allows to send an influence to all players of a role type. For example, a group instantiate the *Production* organisation is linked to all instances of the *Producer* role through the port "producer". The links between groups and roles provide a flexibility in the influences management. An entity has not to know the addresses of the entities playing a specific role before sending an influence. The influence is sent to the group which sends it to the roles.

The link between the micro-level and the macro-level is defined through the ports linking the entities to their roles. A role is linked to an entity through the "player" port. The "player" is an instance of the *RolePlaying* relationship. The port linking an entity to a role is defined through the name of the organisation and the role type name. For example, a Family entity is linked to a Producer role through the "Production@Producer" port. Then, a structure of an entity in OREA allows entities to play simultaneously a same role type in different types of groups.

Table 4.3: The types of port linking the different elements in OREA

	Group	Role	Entity	Aspect
Group		rolename(*) members(*)		
Role	owner	rolename	player	
Entity		groupname@rolename		
Aspect				

The aspects are defined as sub-components of entities. Then, there is not direct links between the aspects and the controlled roles. The aspects interact with roles through the entities. The competences are defined as first class entities executed by the aspects.

4.4.3 The structure of the entities

The internal structure of the entity is managed by a compound object: the *Switch* (Fig. 4.13). The structure of the entity is dynamic. The entity can add and remove dynamically the components (aspects and competences). The components management (adding and removing) is provided by the *Switch*. It manages also the interactions between aspects and their execution.

As noticed previously, the behaviour of entity from the internal point of view is defined by its aspects. The aspects defined by the modeller depend on the domain of interested. In order to provide to entities the capabilities to manage the organisational behaviour (roles handling and interactions management) independently from the domain, a default aspect has been implemented: the `InteractionAspect`. It allows entity to interact with `Model` component to enter or leave roles. The `InteractionAspect` is characterized by a list. When, other aspects require roles, they put the description of the roles (organisation and role type) in this list. At each step, the `InteractionAspect` reads this list in order to get the roles to handle. For each required roles, an influence is sent to `Model` component to get the role. After the roles creation, the `InteractionAspect` updates the list of roles played by the entity. In addition to the roles management, the `InteractionAspect` receives the incoming influences and collects them into the *Switch*.

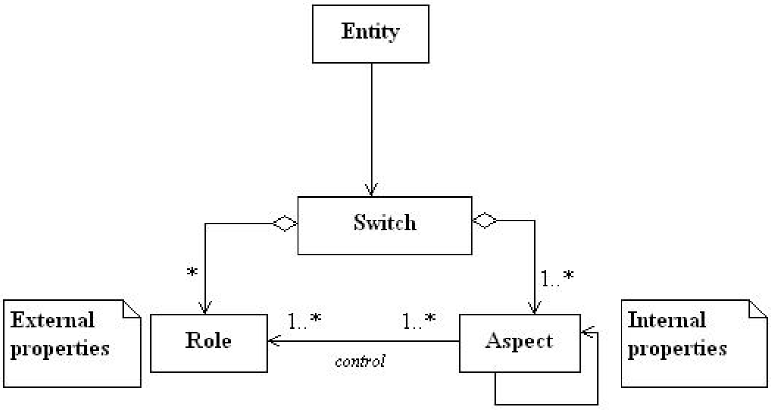

Figure 4.13: Entity internal structure

4.5 The methodology of OREA

Modelling with OREA consists in identifying the different elements constituting a system and their interactions at different scales. Ratzé et al. (2007) gives a description of the notion of scale. A model description with the OREA methodology takes into account both the macro and micro levels (Fig.4.14). The methodology is divided into four parts. The first part describes the scales of description and the underlying processes. The second part describes the system structure and dynamics at the macro-level. The third part provides the micro-level description through the description of entity structures and dynamics. The fourth part provides a textual the description of the global structure. As language, the Unified Modelling Language[1] (UML) and stereotypes are used. The chapter 5 (page 83) provides an application of the OREA methodology.

4.5.1 The identification of scales

The description of a system begins by the identification of the scales of description. The scale identification can be viewed as the definition of the system modelling scope. They define the limits of the modeller observation. The modeller must identify all scales of description and describe their underlying processes. The scales and the underlying processes description is the first step of the organisation and entity description (cf. chapter5 section5.6.1.1 page 96).

[1] http://www.uml.org/

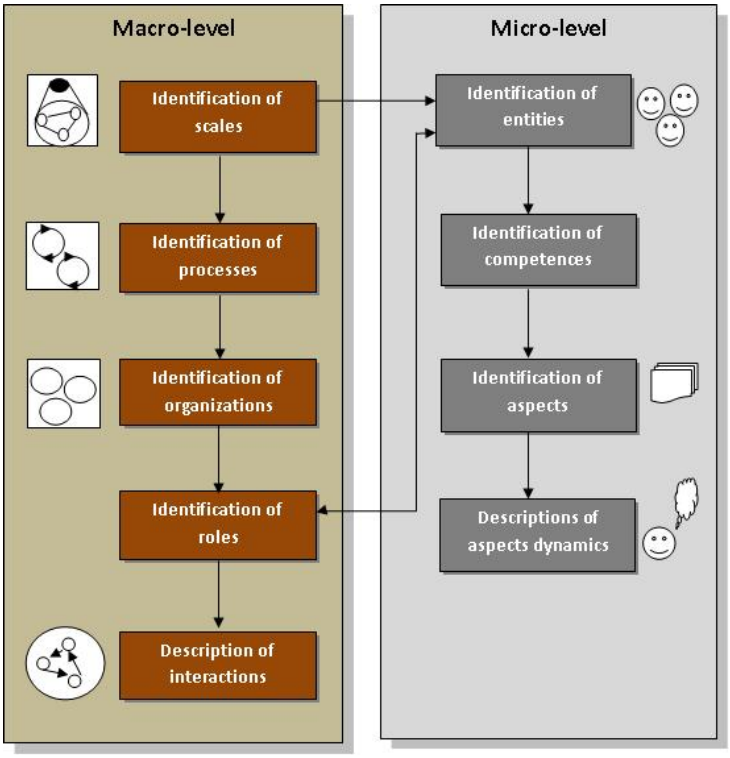

Figure 4.14: The methodology of OREA

4.5.2 The macro-level descriptions

The macro-level defines perception of an external observer on the system. The objectives of the macro-level are to define the "what" without being interested in the "how".

4.5.2.1 The identification of organisation

This step aims at the identification of the organisations. At this step, the modellers identify their points of view on the system at the global level according to their objectives. The organisations identification is based on the processes identified at the last step. The processes are grouped according to the context they describe in order to form organisations (cf. chapter5 section5.6.1.2 page 98).

4.5.2.2 The identification of roles

This step consists in the identification of roles and the description of the organisation structures. The organisation structures are graphically represented as a UML package and the role types are represented as UML classes. The UML *associations* define the relationships between roles (cf.

chapter 5 section5.6.1.2 page 98).

4.5.2.3 The description of protocols

The objective of this step is to describe the interactions from the external point of view i.e how the entities interact among them through their roles. The protocols description in OREA concerns the identification and description of interaction situations. Ferber (1999) defines an interaction situation as follow:

> *"We shall consider an interaction situation as being an assembly of behaviours resulting from the grouping of agents which have to act in order to attain their objectives, with attention being paid to the more or less limited resources which are available to them and their individual skills."*

Many interaction situations can occur in a system. For example, "trading" between a seller and a buyer is an interaction situation as well as a "course" implying teacher and students. The UML sequence diagrams are used to describe the interactions.

The interactions description marks the end of the macro-level description. The next steps aim to the micro-level description in internal point of view.

4.5.3 The micro-level description

The micro-level description is based on the identification of entities , the description of their internal features and dynamics.

4.5.3.1 The identification of entities

The entities are identified through the roles and scales of description. The role describes the abstract function of an entity from organisational point of view. Based on this idea, it is possible to determine the types of entities which behaviour can match with a role according to the studied system and the objectives of the designer. Then, for each identified role, the designer tries to determine at each scale of description, the entities of which behaviours correspond to this role by observation of the real objects in the system. For example, the *Seller* role in the *Market* organisation is an abstract description of selling activity. At the institution level, the entity playing the Seller role can be an enterprise, at the individual level, the entity is a person.

In addition, the scales can be used to determine the entities. For example, a plot defines a spatial scale, but it can be defined as an entity in order to represent the interactions between plots and other entities.

After the entities identification, the designer describes the global structure of the system . The objective is to describe the roles of the entities through the SwimLane diagram. Parunak and Odell (2002) use the Swimlane diagram to define the global structure of a system. A SwimLane diagram is a type of table where the columns specify the organisation schemes and the lines specify the entity types of the system. The intersection between a line and a column specifies the role type played by an entity type within an organisation. The SwimLane diagram allows not only to identify the entity roles but also to describe the organisational dependencies. The dependencies between two organisations are defined through the entity types playing simultaneously roles in these organisations.

The section5.6.1.3 of chapter 5 (page 102) presents an example of identification of entities and the description of global structure using SwimLane diagram.

4.5.3.2 The identification of entities competences

If an entity takes place in an interaction, it has some responsibilities. The entity ability to achieve the responsibilities depends on its competences. The competences identification allows defining the elementary behaviours that the entities need to achieve their responsibilities. The entities competences identification is based on the interactions description. Using the interactions description and the roles of the entities, the designer identifies the entities competences. But the additional competences can be identified during the aspect descriptions.

4.5.3.3 The identification of aspects

The identification of entity aspects is interested in the identification of the non-functional properties of the entities i.e. the properties the entities require to achieve the functional properties from the internal point of view. For that, the entity internal structure is decomposed into a set of aspects. The aspects description consists in the definition of its attributes, the controlled roles, the competences and its dependencies with the other aspects (cf.section5.6.1.4 of chapter5 page106). The relationships between the aspects define the entity internal structure.

The UML package is used to represent the entity structure (cf. page 108). This package is composed of classes representing the aspects and the competences. The roles are represented as the external components of the package. The relationships between the aspects are defined through the UML *association* relationships. The relationships between aspects and competences and between aspects and roles are defined using the UML *execution* relationship.

The aspects and their relationships description provide a static description of the entities. Now, we are interested in the descriptions of their dynamics .

4.5.3.4 The description of entities dynamics

The description of the entity dynamics consists in the description of the aspects dynamics and interactions. The dynamics of aspects description specifies how the aspects react to the internal and to the external events.The StateChart is used for the description of the aspects dynamics. The statechart is relevant to describe the dynamics of an object in the response to the external events. The concurrent stateCharts are used if the aspects dynamics are too complex.

As noticed, previously, the aspects interact between them to share resources and, to provide and to require services. In addition, the aspects receive influences from the roles. In order to describe explicitly the interactions between the aspects and the roles, the UML *interaction diagrams* are used. For each entity type, a single interaction diagram describes the overall interactions links between aspects and roles. The description of the interactions between aspects and roles can be detailed by using UML activities diagrams. For that, the designer identifies the interaction situations from local point of view and describes them through the UML activities diagrams (cf. page 111).

Using the interactions description, the designer defines the aspects and roles dependencies. The dependency descriptions consists in the descriptions of aspects internal and external interfaces. The tables of dependencies are used for that. Two tables of dependencies are used: (1) the aspect-to-aspect table dependencies concerns the dependencies between aspects and (2)the aspect-to-role table dependencies concerns the aspect-to-role dependencies.

The tables of dependencies describe the possible incoming and outgoing influences between aspects and roles. In the aspect-to-aspect table dependencies (Table 4.4), the first column concerns the sources of the influences and the first line concerns the destinations. In the aspect-to-role dependencies table, the first column concerns the aspects and the first line concerns the roles. In the aspect-to-role dependencies table, aspects and roles can be the sources or the destinations of the influences (Table4.5).

Table 4.4: The dependencies between aspects of an entity

	Aspect1	Aspect2
Aspect 1		influence 1
Aspect 2	influence 2	

Table 4.5: Dependencies between aspects and roles of an entity

	Role 1	Role 2
Aspect 1		influence 1
Aspect 2	influence 2	

4.5.4 The identity card of the system

The objective of this step is to describe the identity card of the system. The identity card describes textually the global structure of the system. It summarizes the previous steps in a table (Table 4.6). The identity card of the system provides the description of the organisations through their roles and protocols, the description of the entities through their roles and aspects and the description of organisations dependencies. The organisation dependencies define the relationships between organisations through the roles and entities. These relationships allows to entities of two groups to interact through an entity acting as a mediator.

Table 4.6: The description of the whole system using the identity card

Structure	
Name	The CatMAS
Description	describes the carbon dynamics from from plot to village levels while taking into account the the social, economical and bio-physical factors
Scales of description	plot, farm, village, family, herd
Organisations	Production organisation $\langle\langle Roles : Producer, Product, ProductionSite\rangle\rangle$ $\langle\langle Protocols : cultivation, harvesting, fertilize.\rangle\rangle$ LandTenure organisation $\langle\langle Roles : Allocator, User\rangle\rangle$ $\langle\langle Protocols : plotAllocation, plotHiring.\rangle\rangle$ Transport organisation $\langle\langle Roles : Carrier, Stock, WeatherManager\rangle\rangle$ $\langle\langle Protocols : raining, grazing, erosion.\rangle\rangle$ Transformation organisation $\langle\langle Roles : CompoundProducer, Transformer\rangle\rangle$ $\langle\langle Protocols : Senescing.\rangle\rangle$
Entities	Family entity $\langle\langle Roles : LandTenure < User >, Production < Producer >\rangle\rangle$ $\langle\langle Transport < Carrier >, Market < Seller, Buyer >\rangle\rangle$ $\langle\langle Competences : CultivationSkill, CroppingStrategyChoiceSkill, \rangle\rangle$ $\langle\langle SellingStrategyChoiceSkill, FamilyNatalitySkill\rangle\rangle$ $\langle\langle Aspects : PlanningAspect, SocialAspect, EconomicAspect\rangle\rangle$ $\langle\langle timescales : month, year\rangle\rangle$
Organisations dependencies	Production $\rightarrow$ LandTenure $\langle\langle\{< Family, User >\}\rangle\rangle$

4.6 Conclusion

This chapter presented the OREA model, a conceptual framework to describe a complex system (CS) at different scales of description. OREA allows to describe a CS at the macro and micro levels while integrating the environment. The macro-level is represented in OREA through the notions of organisation and role while the micro-level is defined through the notions of entity and aspect. The macro-level is defined separately and explicitly from the micro-level.

Most OCMAS models fail to deal with the separation of macro and micro levels .In Most models, the behaviour from the organisation point of view and the behaviour from the local point of view are not separated. The roles define both the status and the behaviour of the entities as in Hilaire's proposition and MOCA. In OREA, the roles define the status of the entities within organisation. The entities have their own decision-model defined through aspects. The aspects allow entities to reason about the system and react to the external perturbations. In Gaia, a role defines the behaviour of only an entity type and is more as an aspect. The macro-level does not explicitly defined in Gaia. In Madkit, the roles are implemented in agents structure so that the macro-level is not explicitly represented.

But as Hilaire's proposition, MOCA and Mascaret, the notion of organisation, role are reified. That increases the modularity and the reuse of the organisational structure. We use a component approach to define the internal structure of the entity as in MOCA. The component-approach provides a flexible way to manage coherently and the evolution of the entities behaviour. In addition roles and entities provide competences as in MOCA. But, unlike MOCA, the competences of roles are used by the entities and the role playing is specified in entity internal structure through aspects. This specification allow entities to play differently a same type of role.

In OREA, the environment objects are represented in the organizational structure in order to define explicitly the interactions between entities and their environment and the perception of the entities on their environment depending on their roles. Additionally to a meta-model, a methodology has been proposed. This methodology uses the concepts of UML to describe the structure of a system.

The next chapter presents the application of the OREA model in carbon dynamics modelling from plot to village levels.

Part III

Application of the OREA model

Chapter 5

The conceptual framework of the CATMAS model

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5.1 Introduction

This chapter presents the application of the Organisation-Role-Entity-Aspect (OREA) model and methodology in complex systems (CS) modelling. The objective is to show how the OREA model deals with the multi-scale and multi-point of view description. This application is based on analysis and representation of the dynamics of carbon (C) resources from the plot to the village levels. Using the OREA meta-model and methodology, Carbon Territory Multi-Agent Simulator (CaTMAS), has been designed and implemented. CaTMAS assumes that a better analysis of carbon dynamics at the village level requires consideration of (1) social, economic, physical and biological factors, (2) the individual's actions and the multiplicity of dynamics. The conceptual model of CaTMAS model provides an explicit description of C dynamics at various scales of description. This conceptual model allows a multi-point of view analysis of the C dynamics as organisations made of roles played by entities through various aspects.

This chapter is organized as following. The next section presents the issues of C resources management both at the local and the environmental level. Section 3 describes the C dynamics at the village level and introduces how the computer simulation is relevant to deal with their complexity. In section 4, we review some existing models for simulation of C dynamics and identify their limitations. We explain why the multi-agents system (MAS) is a relevant way to deal with the ecosystem management in section 5. The section 6 describes the CaTMAS conceptual model.

5.2 Issues in the management of carbon resources

The C cycle plays an important role in ecosystem functioning and climate regulation. In the continental biosphere, a third of C is stored in vegetation and the remainder in the soil and in litter (GIEC, 2007). Vegetation and soil contain active pools, the dynamics of which are complex and result from natural and human-driven processes.

The farming systems of sub-saharan African (SSA) smallholders rely heavily on the management of C resources, as endogenous organic matter (OM) is a vital economic good and an essential means of production (Kowal and Kassam, 1978, Dixon et al., 2001). For instance 60% of sub-saharan Africans depend directly on locally grown food harvested from their environment (Dixon et al., 2001). Improvement of food production and other ecosystem services in the short and middle term requires better management of OM resources, nutrients and soil organic carbon (SOC) (Bationo et al., 2007).

At the global level, agriculture, forestry and land-use change impact the concentration of greenhouse gases (GHG) in the atmosphere which drives global climate. Land use change in the tropics (mostly deforestation) accounts for 15-20% of the increase in atmospheric C content (Achard et al., 2004, GIEC, 2003). The environmental effects of land-use change (e.g. on climate or soil quality) are not necessarily immediate; they can occur over a much longer time scale than agricultural processes.

In West-African savannas, local agro-ecological and global environmental issues thus raise the need for acute analysis and prediction of C dynamics.

The village is an operational spatio-functional level for this as many decisions on land use and OM management are driven by communal rules (Manlay et al., 2004b). The C dynamics at the village scale are a complex system and require relevant tools allowing dealing efficiently with their representation and analysis. To deal with the complexity of C dynamics many computer models have been developed to simulate and to predict carbon dynamics. These models are mathematical, process-based or individual-based. Most of them do not (1) include social and economic dimension, not (2) handle system heterogeneity as they do not provide an explicit spatial and temporal representation of C dynamics. In addition, they are too simplified to provide an explicit representation of carbon dynamics at a large scale. The objective of the present work is to propose a model allowing a multiple viewpoint, multi-level analysis and dealing with the system heterogeneity as well as the integration of the social, economic, physical and biological dimensions.

5.3 Carbon dynamics of a village territory in West Africa

The carbon dynamics at the village scale is a complex system since it consists of many entities (soil, plant, farmers, livestock, etc.) interacting at several scales of time and space, carbon resources under multiple uses and management schemas that are influenced by the cropping systems and the population needs.

5.3.1 Carbon dynamics, a multi-scale system

Carbon dynamics occur at three specific spatio-functional levels of description: the plot, the farm and the village levels.

5.3.1.1 Plot level

At the plot level, photosynthesis fixes atmospheric C into the plant biomass (Fig.5.1). During plant respiration C is transferred back to the atmosphere. Senescing biomass turns into litter, which in turn becomes soil organic C (SOC). Other SOC sources include root exudates and animal excreta and tissues. SOC and litter return to the atmosphere as CO_2 or CH_4 during heterotrophic respiration and fermentation. SOC content depends on soil physical, chemical and biological properties and climate as well as past and present land management (e.g. cropping techniques, intensity of wood and crop harvesting, fire management).

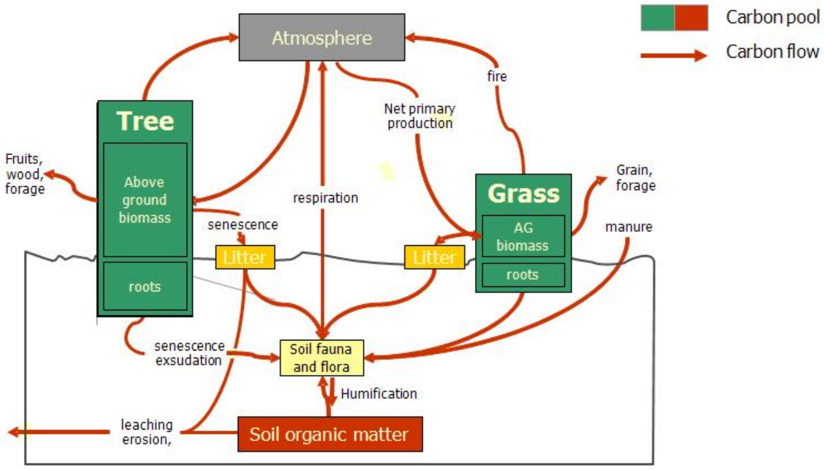


Figure 5.1: Carbon dynamics at plot level in an agrosystem of West-Africa

5.3.1.2 Farm level

At the farm level, rules for the individual management of C resources used to satisfy farm needs are defined and applied. The household aims at securing food and cash needs by managing production. Household decisions and success are driven by several constraints: money, labour power and other means of production. A household is characterized by its population size, labour power, land area, herd composition, strategies of OM management within cropping systems and the production of staple and cash food products. A farm has two main activities: crop production and animal production. Animals account for large OM transfer through ingestion, excretion, and their management (displacement, feeding regime, performances) is determined at the farm level. The farmers take into account the time in their decision-making. Some activities are daily (e.g. the animals management), other are monthly (e.g. crop management depends on the season and months), or yearly (e.g. crop rotation).

5.3.1.3 Village scale

At the village level, interactions occur for transactions of land, manure, labour and for collective rules regarding land use (Fig.5.2). Several groups (e.g. ethnic and social) coexist. Belonging to a group influences access to and use of resources, and the farmers' practices. In addition, the village is an open system that exchanges people, goods and money with outside. These various interactions influence the village organisation, for example emergence of new structures such as farmers or agricultural practices.

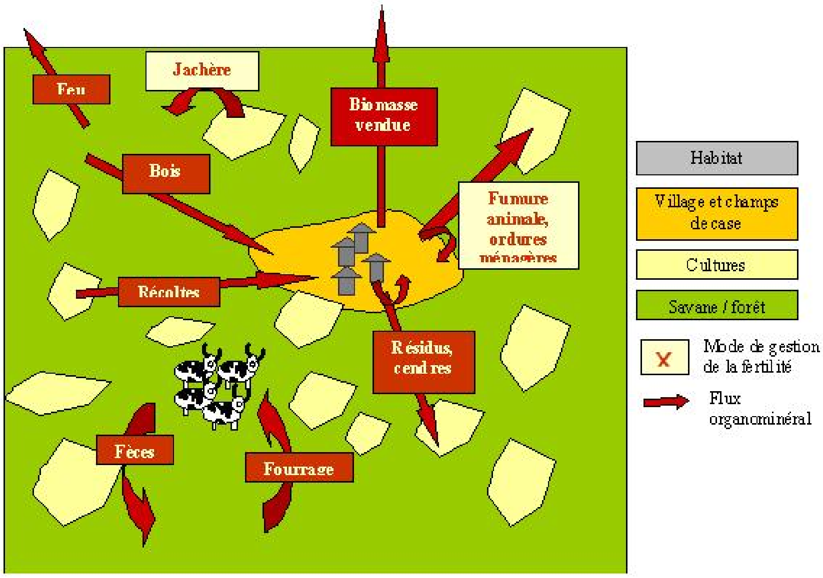


Figure 5.2: Carbon flow at village scale

5.3.2 Functionality

The C resources are means of production because they control the soil fertility and maintain animals which provide labour and transport power (Manlay et al., 2004b). Animals feeding is essentially based on endogenous forage production. The C resources are used for the energy production too in sub-saharan Africa. 90% of sub-saharan Africa domestic consumption of energy is provided by fuel wood (Breman and Kessler, 1995).

Each farming system differs from another; reflecting the heterogeneity of farmers' legacies behaviour and decisions (Valbuena et al., 2008). This heterogeneity is influenced not only by the complexity of the human behaviour itself, but also by both internal and external factors such as land-holders' cultural heritage experience, farm population structure, economic and technical resources, and the socio-economic context where these decisions occur (Valbuena et al., 2008). Various factors - physical, biological, social, economic, cultural-influence C dynamics and they must be considered to realistic simulate C dynamics.

5.3.3 Drivers of change

5.3.3.1 Multiple organic matter managements

In smallholder's farming system of sub-saharan African, the soil fertility is managed through fallowing and application of manure and crop residues. These practices in turn increase soil fertility and biomass productivity. The soil fertility management depends on the farmers' strategies that drive cropping systems and the availability of resources such as land, labour, cash, fertilizers or transport resources. For example, some farmers remove all crop residues to feed animals while others leave them to replenish SOC. In addition, the fallowing depends on the farmers' farm size. The larger the farm more important the fallowing length. The farmers who do not use the fallowing rely essentially on mineral and organic fertilizers to keep their soils fertility.

Carbon resources can be managed in two different ways at a village level: individually (farm management) or collectively. The individual management impacts the collective management and vice versa. For example, biomass intake by individual animals influences livestock growth at village level. In addition, the individual strategies of land-use influence the pastoral activities at the village level.

The decision-making of farmers is complex. It is influenced by many factors: social, economic, biological and physical factors. In addition, the farmers have an adaptative behaviour. They adapt their cropping strategies according to the socio-economic and environmental contexts and learn about their experiences. For example, the farmers change their strategies according to the prices of the crops and fertilizers and take into account the past crops yield to plan the crop production. In addition, the climate change impacts the OM management and cropping strategies.

5.3.3.2 Relation between population and carbon resources dynamics

Demography is an important driver of C dynamics in sub-saharan Africa, the region with highest population growth rate in the world (UNDP, 1999). As population increases, farmers adapt their cropping strategies to meet growing requirements in food and cash . In the first step new land is cleared to increase crop production. When land is no longer available , the cropping intensity is increased at the expense of the fallowing length. Herd size usually increases as long as forage is available. At the plot level, the increase in the cropping intensity reduces SOM levels, perennial vegetation and increases soil erosion. With the deterioration of farming conditions, farmers may change their cropping techniques and adopt new technologies. The farming system deterioration leads also to the increasing of migratory flows and the decreasing of the population growth.

5.3.4 Conclusion

From what precedes, we can consider the carbon dynamics at village territory scale as a complex adaptative system in which the humans are the main actor. The interactions between humans and environment and the uses of the carbon resources are multiple. Through their actions, humans and animals influence their environment which constrains their behaviour. The decision-making of farmers is complex. It is influenced by many factors: social, economic, biological and physical factors. In addition, the farmers have an adaptative behaviour. The underlying dynamics at C dynamics occur at different time scales. Some dynamics can be apprehended only at daily scale (pastoral dynamics, plant growth, etc.) while others are apprehended at monthly and yearly scales (cultivation, population growth, etc.). A realistic representation of C dynamics at village scale should thus:

- include social, economic, biological and physical dimensions.
- take into account the individual actions to underline the heterogeneity of the system with the possibility to analyze simultaneously several organic matter managements.
- include a multiscaling spatial representation. The plot allows tackling how the components interact for C fixation and release, and influence of the organic matter on soil quality (Manlay, 2000). The farm level allows tackling the impact of the farmers' decision-making about the management of C productions. To finish the village territory allows to analysis the viability of the farming systems and interactions between farms for the management of OM resources.

The complexity of carbon dynamics of a village system makes the experiments in the real world at most impossible. Descriptive approaches enable reliable assessment but only for the present or the past. At the plot level, long-term experiments of the effects of OM management on the C balance can yield valid functional models, although they are time-consuming and lack flexibility. But at regional or village level, multiple actors and spatio-functional concerns make computer modelling an appropriate tool for prospective analysis of the C cycle under varying scenarios.

5.4 Computer modelling of carbon dynamics

Several modelling initiatives have been developed to simulate C dynamics and to predict the C status of a system, from the plot to the regional scale. These models can be categorized according to (1) the scale of the model application (plot, farm, village and region) and (2) the modelling method used (mathematical, process-based models, individual-based models).

5.4.1 Process-based models

5.4.1.1 The Century model

The Century model (Parton et al., 1994) - a process-based model analysing and predicting C dynamics in an ecosystem - is a well-known C model. It takes into account the effect of biophysical factors, crop management and grazing on physical and chemical (including SOC) properties of soil. Century contains six submodels:

The SOM submodel: simulates the flows of soil organic matter (SOM) between multiple compartments (Fig. 5.3). The SOM submodel simulates the inputs of plant residues, the organic matter decomposition and flows between soil layers and organic matter pools.

The soil water submodel: simulates the soil water content and temperature. The soil water budget is calculated by taking into account (a) water loss from evaporation and transpiration , water content of the soil layers, snow water content, runoff, and saturated flow of water between soil layers, and (b) the effect of water content on soil texture and vice versa.

The plant production submodel: simulates the dynamics of grasslands, agricultural crops, forests, and savanna systems. The plant production is simulated by taking into account the soil structure, the effect of soil water content and the temperature.

Phosphorus, Nitrogen and Sulfur submodels: simulate the dynamics of these elements.

The Century model is a relevant model to simulate the carbon dynamics at the plot level. It allows representation of external disturbance such as cultivation, tree removal, fire, fertilization and grazing. In addition, the Century model allows simulating the effect of land-use change and organic matter management on SOM and soil texture. But, Century does not include the social and the economic dimensions. It has thus been coupled with economic models (Diagana et al., 2007). However this coupling does not take into account changes in economic context and the adaptation of cropping strategies to these.

Century has been coupled with a geographical information system (GIS) to represent carbon dynamics at a large scale (Paustian et al., 1997, Liu et al., 2004, Easter et al., 2007). The coupling of Century with a GIS allows integrating a heterogeneous environment and simulating simultaneously a variety of soils and cropping systems. A drawback of this coupling is that it is impossible to simulate the cropping systems change in a flexible manner.

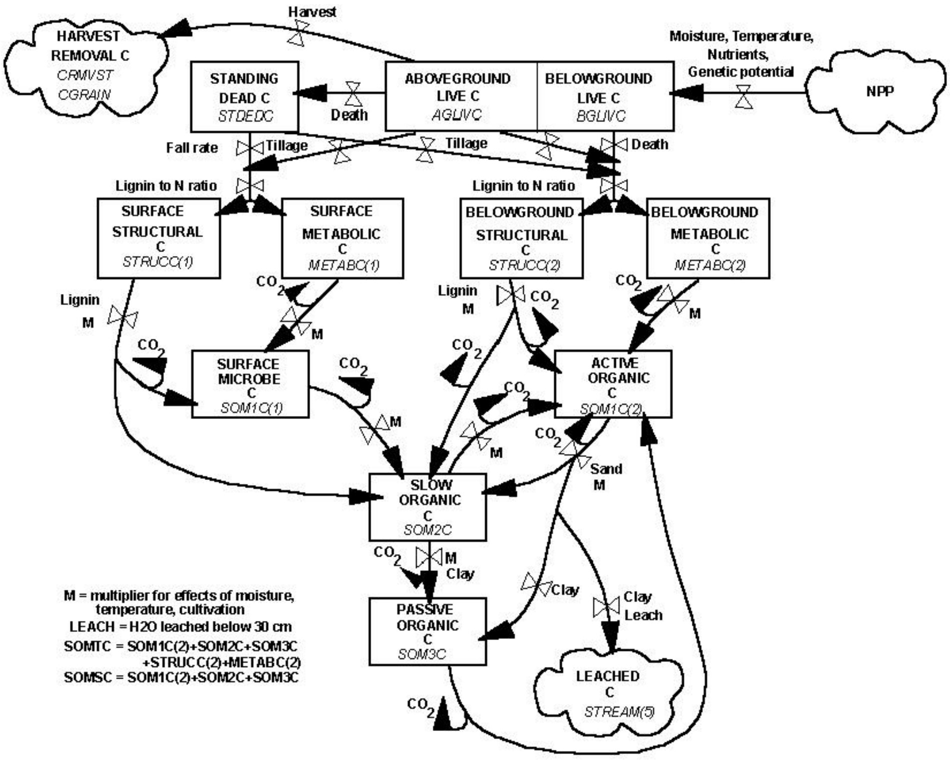


Figure 5.3: Century Soil organic matter submodel

5.4.1.2 The RothC model

RothC (Coleman and Jenkinson, 1996) is a more simplistic model of SOC dynamics. It models turnover of organic carbon in non-waterlogged soils and can simulate the effect of soil type, temperature, moisture content and plant cover on the turnover process. Soil organic carbon is split into four active pools and a small amount of inert organic matter (IOM). The four active compartments are Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM). Unlike Century, Rothc does not simulate the plant growth and residues inputs. Like Century, RothC cannot take into account social, economic factors. But, it has too been coupled with a GIS to spatialize simulation of C dynamics.

5.4.1.3 The Morgan model

Morgan (Balesdent et al., 2000) is a more simplistic model of SOC dynamics that does not include social and economic dimensions. It, too, has been coupled with a GIS in order to represent C dynamics at a larger scale (Falloon et al., 1998).

The process-based models presented in this section provide a relevant framework to represent and to simulate carbon dynamics while taking into account the physical and biological factors. However, these models do not represent the social drivers (interaction, social organisation, activities, etc.) of C dynamics. Today, such drivers requires consideration in C dynamics modelling.

5.4.2 Agent-based models

Belem et al. (2006) proposed the Mirot model, a MAS model that simulates C dynamics in a village of South-West Burkina Faso. The model takes into account three spatial levels: the plot, the farm and the village level. Two cropping systems are represented that can be analysed and compared for their effects on C dynamics. However, Mirot has serious shortbacks: (1) Mirot has been designed for a specific village dynamics and cannot be applied to other villages, (2) it contains a very simplified representation of some dynamics. For example: the model does not include the effect of atmospheric temperature variation on C dynamics; an atmospheric compartment is not included; soil and plant respiration are not represented, the cropping effect on soil is not represented; the crop yield computing does not take into account the bio-physical structure of the soils.

The Mirot experience suggests that MAS can be an appropriate way to deal with C dynamics complexity at a large scale. Carbon dynamics at village scale is a complex system (cf. section 5.2 page 84). Using MAS, it is possible to take into account the heterogeneity within and among farming systems, the self-adaptive behaviour of the farmers and the impact of social dynamics on C dynamics (cf. chapter 3 page 21). Supporting an explicit representation of the environment, the MAS allow dealing efficiently with the spatial dynamics of C dynamics (C pools distribution, pastoral dynamics and land-use).

5.5 MAS and ecosystem simulation in environmental sciences

The dynamics of a renewable resource is the object of a triple complexity: (1) ecological, (2) social and (3) the one resulting interactions between those on which the economic, social and ecological viabilities of the system depend. The ecosystem is an opened, self-adaptative, self-organising system. Human as part of the system, interact, learn, adapt their behaviour and anticipate the future. The humans interact within a social organisation which constrains their decision-making. This organisation evolves in time. In addition, the ecosystem is non-linear. It is impossible to determine *a-priori* the state of such systems. The representation of such system requires considerations of the entities, the nature of relations and interactions among them and the organisational properties of the system:

> *"To study these systems, the observations focus on the connectivity of the ecosystem's elements, their interactions, and their organisation across various scales"* Bousquet and Le Page (2004).

Research in ecosystem management is interested in the prediction of the system behaviour, the heterogeneity of the system, the individual decision-making, their interactions, the social organisation and dynamics, the diffusion of technology , the coordination and learning in resources management, the spatial dynamic, etc. Computer simulation is relevant for that. Several simulation approaches have been proposed: mathematical modelling, the CA, the IBM and the agent-based or MAS modelling. As show bellow, MAS meet most requirements (cf. section 2.5 page 18 and section 3 page 21) for modelling ecosystem management identified above.

5.5.1 MAS and social simulation

As noticed previously, the ecosystem management requires consideration of the social dynamics. The social simulation (Gilbert, 2004) is one of the more important application domain of the MAS. MAS provide a flexible way to define explicitly the social organisation (Amiguet et al., 2003, Ferber and Gutknecht, 1998) and dynamics. Individual agents can be used to represent an individual people, individual agents can be used to represent organisations and similar such entities (Wooldridge, 2002). Amblard and Ferrand (1998) use the AGR formalism to simulate change in the social network in a farming system. Conte and Gilbert according to Wooldridge (2002) suggests that multi-agents simulation of social processes can have the following benefits:

- the computer simulation allows the observation of properties of a model that may in principle be analytically derivable but have not yet been established;
- possible alternatives to a phenomenon observed in nature may be found;
- properties that are difficult/ackward to observe in nature may be studied at leisure in isolation, recorded, and then 'replayed' if necessary;
- 'sociality' can be modelled explicitly - agents can be built that have representations of others agents, and the properties and implications of theses representations can be investigated.

5.5.2 Coordination of the resource management

When the resources are subject to common use, the stakeholders may coordinate their activities. However, stakeholders do not necessarily share the same strategies and objectives. It is thus necessary for them to exchange information about their strategies and take decisions.

Agents in MAS can make decisions by taking into account their own strategy and the strategies of others agents (Barbuceanu et al., 1998b, Jennings, 1996). They can coordinate their activities for a better use of a resource. Their decisions can be individual or collective. Barreteau and F. (2000) build a MAS model to analyse the viability of an irrigated system in Senegal. In their model, the farmers coordinate their activities, exchange information for the common use of water resource.

5.5.3 Modelling of policy and learning

Scientists and decision-makers working in ecosystem management must consider the impact of the stakeholders management rules on the resources. Their objective is to identify the management rules which allow a best use of resources according to specific criteria. However, the stakeholder's decision-making is complex. In addition, there is a variety of decision rules. For example, in a farming system, several cropping systems can influence land-use and its change. It is necessary to study the performance of each cropping system and its impact on the resources dynamics. The farmers' decision making is motivated by the farmers' objectives and several factors (labour, farm size, distance from residence, etc.). In addition, the farmers have an adaptative behaviour, they learn about their experience to improve their decision making.

The agents in MAS can capture complex decision model. Each agent has a decision model which allows it to take decision and achieve its goals in different situations. Agents make decisions according to their internal state and perception on the environment. In addition, they can learn about their experiences in order to adapt their decision-making (Gies and Chaib-draa, 2004) and achieve successfully their goals. In addition they can take into account the strategies of others agents to improve their decision making. MAS for the simulation of resources management have been applied to a large range of issues such as analysis of the farmer-specific relationships between landscape and land use Bakkera and van Doorna (2009), simulation of the collective learning for ecosystem management Bousquet et al. (2002a), assessing of the climate policy using MAS Dowing et al. (2001) or simulation of the fisheries management Bousquet et al. (1994).

5.5.4 The environment dynamics

The environment plays an important role in the CS. For example, C cycling at the territory village scale includes the C flows from and to soils. The soil carries carbon resources being the subject to multiple uses by the various actors of the system. The soils at a village vary (e.g. in their type, texture or mineralogy). The spatial distribution and properties of soils influence largely the individuals' decision making (e.g. cropping strategy, the pastoral strategies). For a realistic representation of the ecosystem, the environment and its interaction with the entities of the system must be explicitly represented.

MAS support environment representation (cf. section 3.5 page 26). Environment can be a space where the physical activities of the agents take place. The agents can perceive and modify their environment through their actions. Then, the use of MAS makes possible the representation of the interaction between human and their environment.

Bithell and Brasington (2009) investigate how demographic changes influence deforestation and assess its impact on forest ecology, stream hydrology and changes in water availability. Bonnefoy et al. (2000) simulate the interactions between social and spatial dynamics using MAS. Lardon et al. (1998) simulate the effect of farming dynamics on the landscape transformation.

Using MAS approach and the OREA model, we define the conceptual model for the C dynamics at different scales of description.

5.6 Conceptual description of the CaTMAS model

In this section, we present the description of conceptual model of the CaTMAS. Conceptual model helps to problem understanding and solution proposal Diest et al. (2000). It is essential for :

- *Making real-world concepts and relationships tangible. " Recording parts of reality that are important for performing the task in question, and downgrading other elements that are insignificant.*
- *Supporting communication among the various "stakeholders" (customers, users, developers, testers, etc.).*
- *Detecting missing information, and errors or misinterpretations, before going ahead with system construction.*
- *Providing an orientation on how the software should meet a need.*
- *Providing a specification of the behaviour of the system under construction.*

Diest et al. (2000).

The conceptual model must be expressed using a specific language. According to Shannon (1998), *"The conceptual model formulation allows Developing a preliminary model either graphically (e.g. block diagram or process flow chart) or in pseudo-code to define the components, descriptive variables, and interactions (logic) that constitute the system."*

We use the OREA meta-model and methodology (cf. section 5.6 page 95) and the UML concepts and stereotype to describe the CaTMAS conceptual model. The proposed conceptual model allows a multiple points of view analysis of C dynamics as organisations made of roles played by entities through various aspects. The model structure is based on six organisations, specifying the system functionalities: "Land Tenure", "Production" (for plant and animal productions), "Transport" (for organic matter -OM transfers), "Transformation" (for OM production and decomposition), "Market" for resource exchange and "Mobility" for the spatial dynamics. At the individual level, two categories of entities are represented: (1) the OM users: "Actor" representing a person, "Family" specifying a group of persons and "Herd"; (2) the entities directly involved in the OM cycles: "Plant", "Soil" and "Climate".

5.6.1 Functional structure

5.6.1.1 Scales of description

According to the OREA methodology, the conceptual model description starts by the identification and the scales of description and the underlying processes (cf. section 4.5.1 page 74). The objective of this section is to describe the processes in which we are interested at different scales of description. We identify seven scales (Table 5.1) from the spatial and social point of of view. From the spatial point of view, the carbon dynamics can be described at plot, farm and village scales. The plot level allows tackling how the different entities interact in order to produce the C. At the plot level, the C dynamics concerns plant and OM productions, the OM decomposition, water storage in the soil. The farm scale allows(1) analysing the impact of the land-use change rules and fertility management on the C dynamics and (2) defining the scope of a farmer's decision rules. At the village level, we are interested in the analysis of the viability of the farming systems and the interactions between stakeholders for the organic matter management, the labour and lands agreement, and the impacts of climatic and economic changes.

At the farm level, we assume that the decision is collective. The land-use change and fertility management are driven by the households. Each member of the household provides labour power force crop production and plays an important role in the household dynamics (birth, death, food consumption, etc). Then, two levels - individual and family - describe the system from the social point of view.

TO represent the role of animal production in the C dynamics, we identify two scales: "individual animal" and the "herd" scales. These scales are important from the biological and economic points of view (Breman and Ridder, 1991). From a biological point of view, the objective is to know the connections between the individual animals and the herd. The individual animal plays an important role in preservation of the animal population . The animal population growth depends on the individual animal fecundity. But the individual animal characteristics are driven by the nutritional status which depends on the animal population size. The average production per animal increases with the improved supply of fodder. Conversely, the production decreases which the deterioration of the nutritional status. From the economic point of view, the herd is the most common management unit in extensive farming systems; the primary requirement being that this unity is sufficiently productive to allow the owner and his family to have an adequate income (Breman and Ridder, 1991).

Table 5.1: The scales of observation in carbon dynamics at village scale

Scales	Process
Plot	plant production organic matter production organic matter storage water storage organic matter decomposition
Farm	land-use change rules fertility management
Village territory	organic matter market labour force exchange land exchange (plot allocation, purchase, hiring) climate change global economy change
Person	aging, birth, death, migration
Family	economy of households animals production cropping system migration
Animal	cycle of production (aging, birth,death, growing,selling,purchase)
Herd	pasture dynamics

The scales of description allowed determining the scope of our study while the description of the processes allowed determining the functionalities of our model. At each role, some responsibilities are associated. Now, we will identify the points of view (organisations) in order to specify the organisational structure of the model and the description of the roles.

5.6.1.2 The organisational structure of the model

This section is interested in the organisations identifications and their structure description (roles identification). This section includes the second and the third step of OREA methodology (cf. sections 4.5.2.1 and 4.5.2.2 page 75). An organisation define a point of view of the system at the global level. The identification of organisation is based on the scales of description and their underlying processes.

The processes identified in the previous step have been grouped according to the properties they describe at the global level (Table 5.2). Then, plant production, land-use change, fertility management and cropping system processes describe plant production. The animal production by the household and the animal cycle of production describe the "animal production". The decomposition and production of OM at plot level describes the "OM transformation"'. The pasture dynamics of the herd, the storage of OM and water describe at the global level, the C resources transport (transfer). In addition to these organisations, a spatial organisation has been defined in order to provide a conceptual representation of the physical environment.

Table 5.2: The identification of organisations through the scales of description and their processes

Organisation	Process
Land tenure	land allocation
Plant Production	plant production land use change rules fertility management cropping system
Animal Production	animal production animal cycle of production (aging, birth, death,growing,selling)
Transformation	organic matter decomposition organic matter production
Transport	organic matter storage water storage pasture dynamics
Market	organic matter market labour force exchange land exchange (purchase, hiring) global economy change Animal selling and purchase

As noticed previously, the organisation describes the relationships and interactions among the entities through the notion of role. A role describes a function of an entity in the system. After the organisations identification, we process to their roles identification and the relationships of roles descriptions.

The LandTenure organisation

The **LandTenure** organisation describes the land-grabbing. It describes the relationships between the farmers and the land. In addition it defines the laws governing the land use. Three role types compose the **LandTenure** organisation (Fig.5.4):

The *Allocator* role has the responsibilities to share the plots between the land users. It controls the laws governing land-use. The Allocator manages the request of several applicants wishing to use some land.

The *User* role controls the allocated lands. The relationships between the user and the land determine his rights on the land. We identify several rights: own, hire, selling, uses rights. An user with the own right has the hiring, the selling and the use rights. Any User can produce on Land.

The *Land* role the part and the land to allocate. The *Land* role is in relation with the *Allocator* role and with the*User* role.

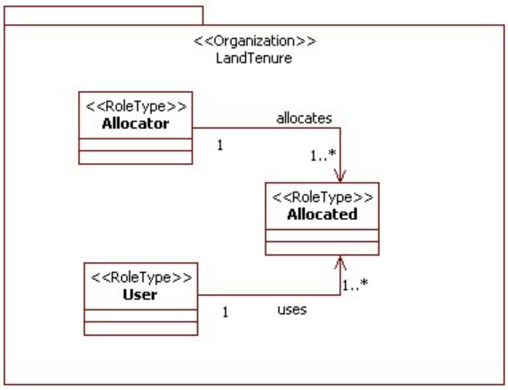


Figure 5.4: The UML representation of the *LandTenure* organisation

The Production organisation

The **Production** organisation describes the interactions between the farmers and the environment for the animal and crop production. We identify three roles to describe the **Production** organisation (Fig.5.5):

The *Producer* role manages the production by interacting with the *ProductionSite* role. The *Producer* role allows to interact with the environment for the crop production (plant, crop, harvest, etc) and the animal production.

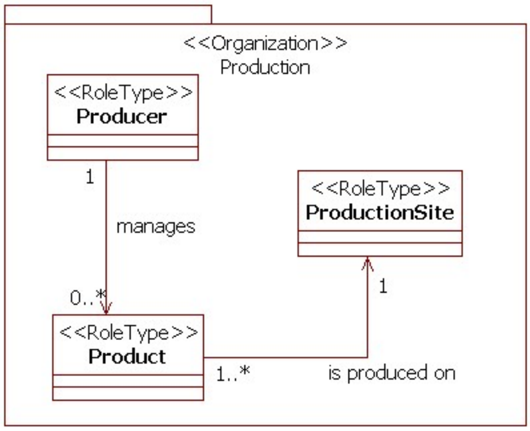


Figure 5.5: TThe UML representation of the *Production* organisation

The *Product* role describes the external dynamics of the objects under production (plant, animal). The *Product* role interacts with the *ProductionSite* role to uptake resources (water, nutriments, etc.).

The *ProductionSite* role designates the place of production. The *ProductionSite* role can be viewed as an environmental role. It provides resources for the *Product* growth and allows the *Producer* to manage the production.

The Transport organisation

The **Transport** organisation organisation describes how the entities interact for the carbon resources storage (water, OM, carbon, etc.) and transport (erosion, animal intake, etc.). In other terms, the **Transport** organisation is interested in C flows between entities. Some entities interacting in **Transport** organisation uptake the resources, they are considered as the C resources carrier, other provide and store the C resources, they are considered as stock. We identify three role types to describe **Transport** organisation (Fig.5.6):

The *Carrier* role transfers resources from one place (*Stock*) to another (*Stock*). It has the responsibilities to uptake and provide the C resources by interacting with the *Stock* role.

The *Stock* role allows entities to store and provide resources (water, N, etc). It provides stored resources (N, CO_2, C, etc) to the *Carrier* role. It can also receive resources from the *Carrier* role and water from the *WeatherManager* role.

The *WeatherManager* role rules rainfall and temperature variation. The water produced is stored by the *Stock* role.

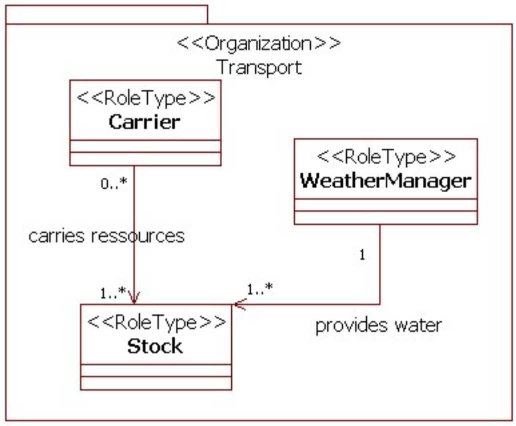


Figure 5.6: The UML representation of the *Transport* organisation

The Transformation organisation

The **Transformation** organisation describes how the entities behave and interact for OM transformation. The **Transformation** organisation is composed of the following roles (Fig.5.7)

The *CompoundProducer* role deals with the production of the litter that will be transformed into OM.

The *Transformer* role has in charge of decomposing organic matter. The transformer decomposes SOM and litter produced by the compound producer.

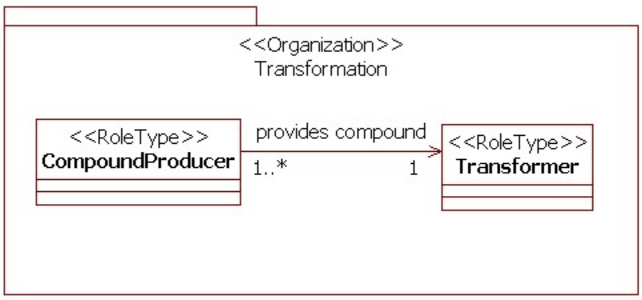


Figure 5.7: The UML representation of the *Transformation* organisation

The Market organisation

The **Market** organisation describes the economic activities of the entities i.e. their interactions for trading of OM, crops, land or animal. Two roles describe the **Market** organisation: (Fig.5.8): *Seller* role and *Buyer* role interacting for trading of resources.

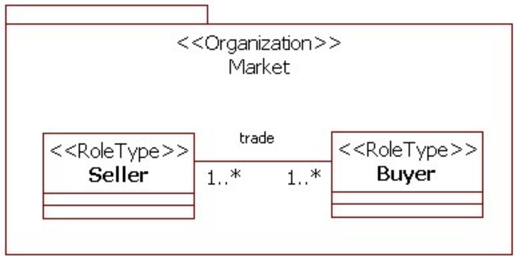


Figure 5.8: The UML representation of the Market organisation

The Spatial organisation

The **Spatial** organisation describes the physical environment. The **Spatial** organisation describes the elements embedded in the environment, their relationships and interactions. The environment is organised through the relations between the *Space*, *Place*, *Object* and *Resource* roles (Fig.5.9):

the *Space* role describes the whole environment where the interactions take place. The space is composed of places, objects and resources that interact among them.

Place role defines the location of objects and resources in the environment. A place is related to other places that determine its neighbourhood. It can interact with the objects and resources that it supports.

the *Object* role allows entities to perceive the environment and to move. *Object* interacts with *Place* role to perceive its neighbourhood or to find objects and resources at a specific location.

the *Resource* role: the objects interact with the *Resource* role in order to access and modify the state of the entities playing it. But the entity state is not directly modified. The entity playing *Resource* role controls its own state.

The descriptions of organisations and roles allowed to specify the structure of the model at the macro-level. To fulfill the conceptual model description, we must describe the micro-level and its relations with the macro-level. The next steps focus on description of the micro-level through description of entities and aspects .

5.6.1.3 The entities of the model

According to the OREA methodology fifth step (cf. section 4.5.3.1 page 76), the identification of entities is based on the scales and the role descriptions. Some scales identified previously are

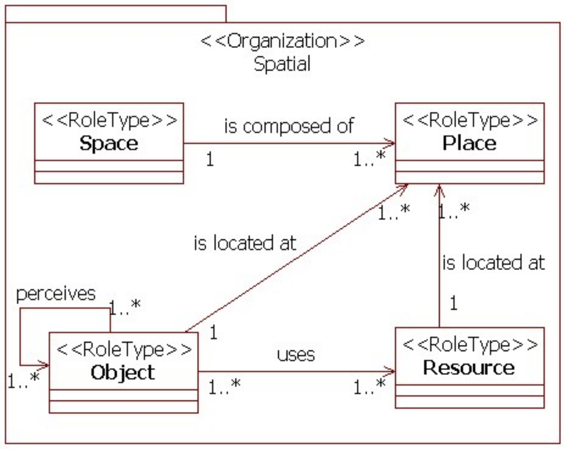


Figure 5.9: The UML representation of the Spatial organisation

transformed into entities. The family, plot, the village and the herd scales become full-fledged entities. As to animal scale,it is not represented as entity because, we are not interested in the animal representation as individual entity. It is defined in the internal features of **Herd** entity entity.

Two categories of entities have been identified. The first category concerns the users of the organic matter: the **Actor** entity standing for a person, the **Family** entity specifying a group of person sharing the same farm and using the same resources and the **Herd** entity specifying a group of animals. The second category of entities are directly concerned by the cycling of organic matter: **Plant** entity, **Soil** entity and **Climate** entity. The whole system is represented through the **VillageTerritory** entity, it is concerned by the two categories.

After, the identification of types of entity of CaTMAS, we are going to describe their behaviour. OREA assumes that an entity provides an external and an internal behaviour. The external behaviour is defined by the roles played by the entity while its internal behaviour is defined by the aspects. The roles determine the observable behaviour of the entities. They allow entities to be in relation and interact between them. The roles of different entities identified are defined as follow:

The Actor entity: plays the *Allocator* role for the management of the land use.

The Family entity: manages the crop and animal production through the *Producer* role and fertilizes the soils using the *Carrier* role. It buys and sells crops and animals through the *Seller* and *Buyer* roles. From the spatial point of view, the spatial behaviour of the **Family** entity is defined by the *Object* role

The Herd entity: The Herd entity plays *Product*, *Carrier* and *Object* roles. The **Herd** entity intakes plant biomass and excretes urine and faces through the *Carrier* role. Using the *Object* role, it can perceive the environment, the resources and move in the environment.

The VillageTerritory entity : represents the system in which all dynamics occur. **VillageTerritory** entity is the environment of the system. It holds *Space* role.

The Soil entity: is a spatial entity where the physical activities take place. The **Soil** entity participates in the organic matter storage and decomposition, the water storage and the plant growth. The **Soil** entity plays *Place*, *ProductionSite*, *Storage* and *Transformer* roles.

The Plant entity: represents a population of plants (cropped or not, herbaceous or woody). It plays *Product*, *CompoundProducer*, *Object* and *Resource* roles.

The identification of the entities roles allowed determining the global structure of the system (Fig.5.10) (cf. section 4.5.3.1 page 77). The global structure is described using the SwimLane diagram which defines the roles (cells of the table) of entities (lines) within organisations (columns). If two entities play a same role, this role is put on the lines of the table. At this stage, we were interested only in entity description from the external point of view, what they have to do in the system in order to fulfil the objective of the system. The next sections describe the entities from the internal point of view, how they behave internally and react to the external perturbations.

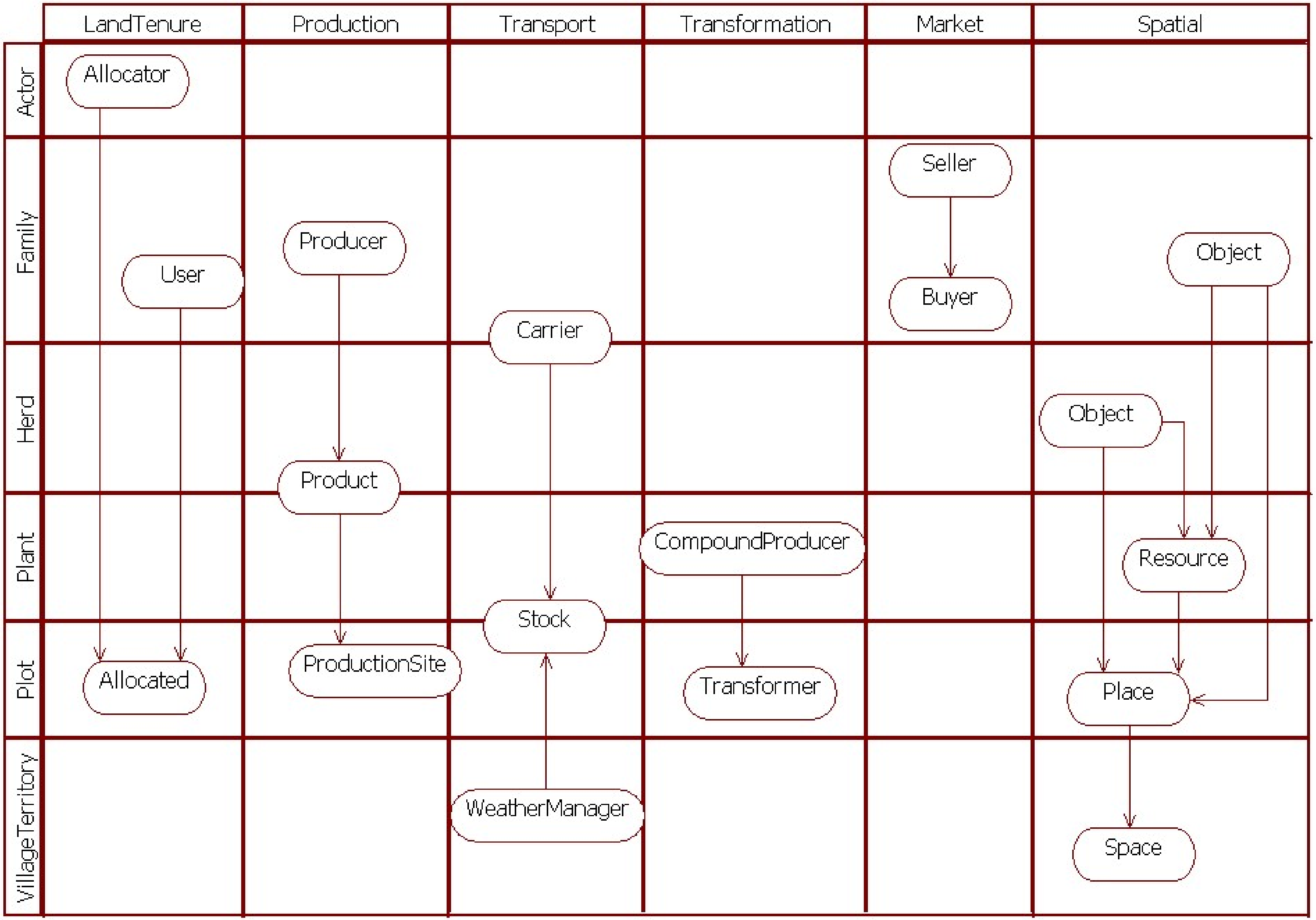


Figure 5.10: The CaTMAS global structure

5.6.1.4 The aspects of the entities

The aim of this section is the identification of the aspects of entities. This section includes both the three last steps in OREA methodology (page 77 to page 78).

The descriptions of the aspects consist in the description of the entities behaviour differently from their organisation behaviour (roles). They determine how the entities reason, make decision and react to the external perturbations. Unlike the roles, the aspects are not visible by the other entities. Each aspect is described through a set of attributes, and controlled and required competences. The competences define the capabilities of the entities to achieve some services. They allow entities to reason about the behaviour of other entities for a coherent behaviour.

In this section, only the aspect of **Family** entity and **Herd** entity are described.

The aspects of Family

The human activities are represented through the **Family** entity behaviour. The **Family** entity behaviour is characterized by its decision rules for crop and animal production, energy use and the economic behaviour. It resumes the main factors to take into account in our study: social, economic and biological factors. To represent how the **Family** entity behaves, the following aspects have been identified:

PlanningAspect describes how the **Family** entity plans crop production and uses resources to achieve its objectives (cash, food, etc). In other terms, the *PlanningAspect* defines the **Family** entity cropping strategies: how the family determines the area to cultivate for each type of crop, how it defines the farming calendar and applies the cropping techniques. The *PlanningAspect* is characterized by the labour power, available plots, organic and mineral fertilizers, food and money needs and the types of cropping systems. The *PlanningAspect* uses the *Producer* role to manage the production and the *Carrier* role for the fertilization of plot.

SocialAspect describes the social features of the **Family** entity. Demography evolution is specified through the *SocialAspect*. It represents the food consumption, natality, mortality and immigration. The *SocialAspect* requests also plots for the **Family** entity through the *User* role.

EconomicAspect specifies the economic behaviour of the **Family** entity. It defines how the **Family** entity manages cash and food, invests in animals, equipment and land. It controls the *Seller* and *Buyer* roles. It is characterized by the cash and the resources to buy.

Several competences have been identified to describe the **Family** entity capabilities to achieve some tasks through the aspects. These competences are used to specify the dynamics (Table 5.3 ,Fig.5.11):

The *PlanningAspect* defines the production through the *CroppingStrategyChoiceSkill*. Depending on the available labour power and land, the level of equipment, the crop sharing, thus competence determines the area to cultivate for each crop and required labour. The crop production management (planting, cultivation, harvest, etc.) is achieved through the *CultivationSkill*. This competence defines the cropping calendar and achieves the cultivation tasks until the crop harvest. Using the *SellingStrategyChoiceSkill*, the *PlanningAspect* defines the selling plan. The *SellingStrategyChoiceSkill* defines for each crop the quantity to sell according to the crops production, the cash and food needs and the crops sharing. The definition of cash need and the crop selling are achieved by the *EconomicAspect* by using the *CashManagementSkill* and *PurchaseSkill*. The *CashManagementSkill* defines the cash need, the employees payroll and the investment plan. The *PurchaseSkill* handles purchasing crops, equipment, animals, etc. according to the investment plan. The *SocialAspect* controls the food consumption through the *EnergyManagementSkill* and the dynamics of **Family** entity local population through the *FamilyNatalitySkill* competence.

Table 5.3: Description of the Family entity through its aspects, roles and competences

Aspect	Competences	Roles
	CroppingStrategyChoiceSkill	Producer
PlanningAspect	SellingStrategyChoiceSkill	Carrier
	CultivationSkill	
SocialAspect	FamilyNatalitySkill	User
	CashManagementSkill	User
EconomicAspect	PurchaseSkill	Buyer
		Seller

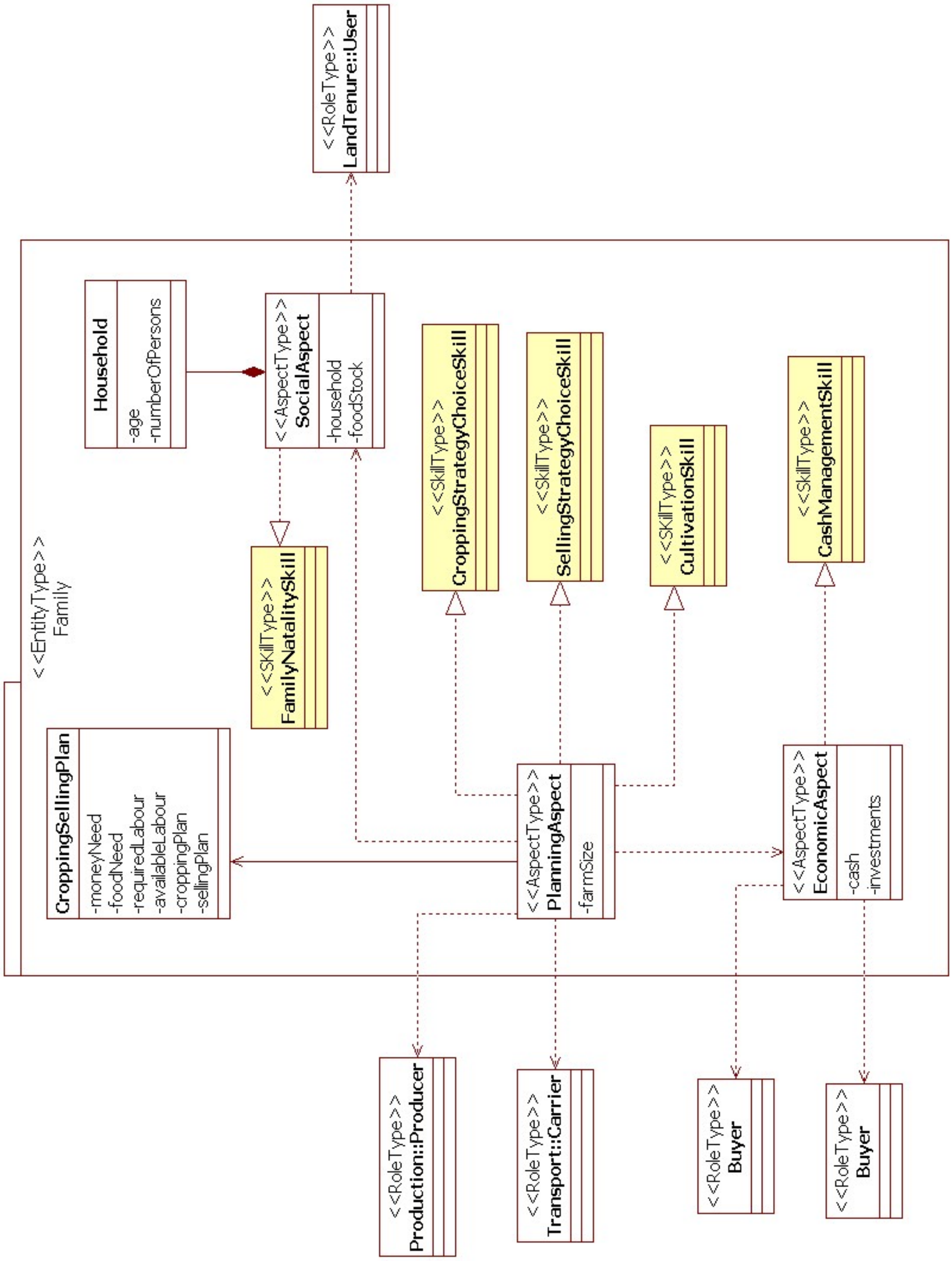


Figure 5.11: UML Graphical representation of Family entity from local and external points of view

The aspects of the entities interact internally between them and with roles to share information, to request services or to achieve specific tasks. For example, Fig.5.12 describes the interactions between the aspects and roles of the **Family** entity for the crop production. The entity behaviour arises from these interactions and the aspects dynamics. The interactions link define the dependences between aspects and between aspects and roles. These dependencies must be explicitly described for a coherent behaviour of the entities. These dependencies are expressed using the notion of influence. Several interaction links have been identified to specify the **Family** entity behaviour. The Table 5.4 and Table 5.5 describe respectively the dependencies between aspects in one hand and between aspects and roles in other hand. For example, *PlanningAspect* is linked to *SocialAspect* by the "storeCrop" influence. The interactions links between aspects of the **Family** entity is graphically represented by the Fig.5.13.

Table 5.4: Dependencies between aspects of Family entity

Aspects	PlanningAspect	SocialAspect	EconomicAspect
PlanningAspect		storeCrop getHouseHoldSize	calculateCapitalProduction sellCrop getCash invest
SocialAspect	householdSize		buyCrop
EconomicAspect	availableCash		

Table 5.5: Dependencies between aspects and roles of Family entity

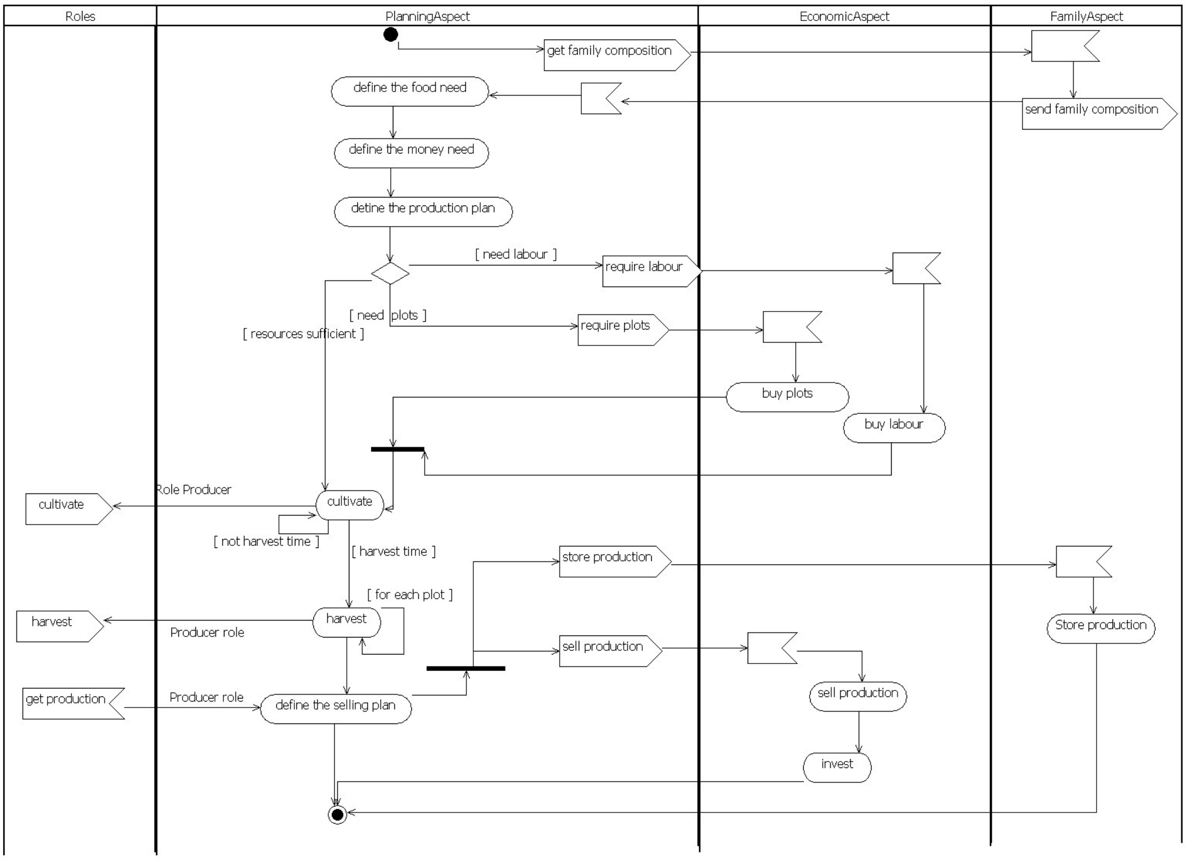
Aspects	*Roles*			
	Producer	Carrier	Seller	User
PlanningAspect	cultivate harvest putPlotInFallowing	removeTree transportResidue addFertilizer		
SocialAspect				requestPlot
EconomicAspect			sellCrop buyFood	

The aspects of the Herd entity

The CaTMAS model is interested in the recycling of carbon resources by the animals including the intake and the excretion and energy transformation for animal growth. The Herd has a spatial dynamics which characterizes the carbon resources transfer. The Herd behaviour is represented with two aspects: *PastoralAspect* and *SpatialAspect* aspects (Fig.5.14):

The *PastoralAspect*: specifies how the **Herd** entity participates into the organic matter transfer and transformation. It describes the pastoral dynamics (grazing, excretion and energy transformation), the herd growth. It is characterized by the herd size, the grazing length and duration, the intake and the quantity of OM and urine excreted. The *PastoralAspect*

Figure 5.12: The interactions between aspects from the local point of view on the Family entity



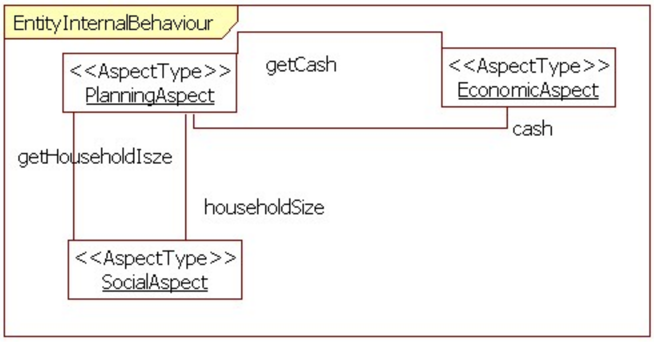


Figure 5.13: The behaviour Family entity from the local point of view

controls *Carrier* and *Product* roles and requires the *GrazingSkill*, *EnergyTransformationSkill* and *GrowthSkill*. The *GrazingSkill* achieves the biomass intake and the excretion. The *EnergyTransformationSkill* transforms the forage into energy required for the increase in animal mass and maintenance. The birth and death of animals are achieved through the *GrowthSkill* competence.

The *SpatialAspect*: specifies the spatial behaviour (environment perception and moving) of the **Herd** entity. It controls the *Object* role and requires *PerceptionSkill* and *MovingSkill* competences.

Through the aspects identification, we conclude that aspects are the modular unit implementing a concern from an entity point of view. In many OCMAS models, all properties of the **Family** entity will be defined in a single entity as in OOP. In OREA, the entities attributes and behaviour are distributed among aspects. Then, two instances of **Family** have not necessary the same behaviour and attributes. For example, if a **Family** entity does not produce crops, it cannot handle the *PlanningAspect* which represents the cropping behaviour. In addition, the aspects allow to separate the entities behaviour from their organisational behaviour specified by the roles. That ensure the coherency of the entities behaviour. For example, the **Family** entity plays *Seller* and *Buyer* roles, using the aspects it is possible to control the dependencies between these roles in case where the buying activity depends on the selling activity.

5.6.2 Dynamics

This section is interested to the Family and the Herd entities dynamics description.

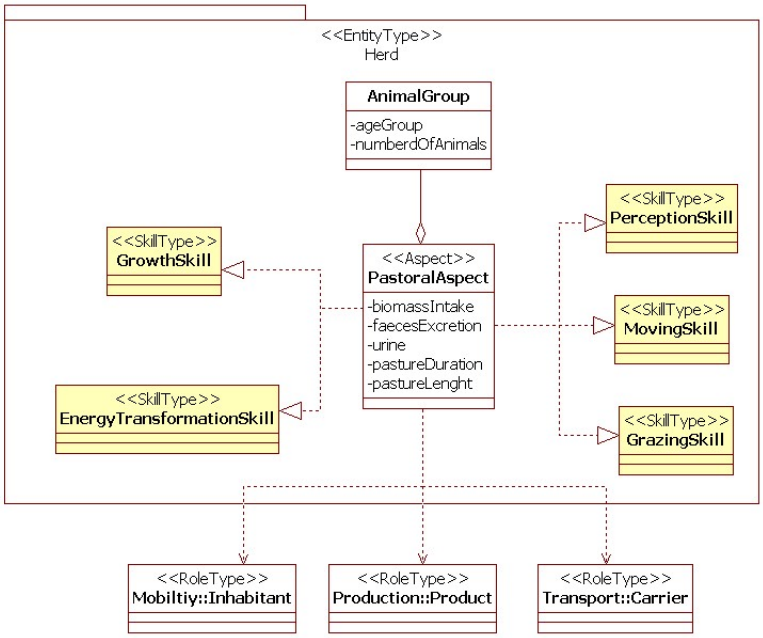


Figure 5.14: The description of Herd entity from local and external points of view.

5.6.2.1 The entity Family dynamics

Natality and ageing

The family is structured as a collection of groups with respect to age classes. Each year, the age of each group is incremented. The natality is a function of the gender ratio and the fecundity of the age class. From fecundity, birth occurrence is then determined through a random value. Natality decreases if the food production does not meet food requirement of the population and increases otherwise.

Mortality

Mortality is a function of the mortality rate of the age class. Each year, a random value determines the mortality in a group. The mortality rate evolves according to the population size and the food production. It increases if the production does not meet the food requirement of the population and decreases otherwise.

Production

The **Family** entity aims to satisfy its food and cash needs depending on its size. For that, **Family** entity defines a production plan. A production plan defines the area to be cultivated for each type of crop according to the previous yields of the crops. It depends on resource (labour, land, fertilizer) availability. After planting crop, **Family** entity controls the production until the harvest time. The production management will partly influence the crop yield. For that, it follows a crop-specific farming calendar. Then, each month, the labour timetable is scheduled.

After the harvest, **Family** entity sells a part of the production. For that, it defines a selling plan. A selling plan defines, for each crop, the quantity to sell according to the production, the price of the crop and the share of the crop in the **Family** entity consumption. If cash and food needs are satisfied, the **Family** entity can invest in animal production or in production means.

Food consumption

Family entity consumes food to its meet energy requirement. The energy requirement is a function of the **Family** entity structure since it depends on individual age class. The crops are used according to their share in **Family** entity consumption. If the food is not sufficient, it gets it from the market.

Emigration and Immigration

The population growth is not strictly endogenous. The model takes into account the emigration and immigration. Emigration is a function of the emigration rate of each age class. Each period (year), according to the structure, we use a random value to decide the departure of an individual in an age class. The emigration rate evolves in the same way as the death rate.

Immigration represents the creation of new **Family** entity. The **Family** entity creation is function of the arrival occurrence. At each cycle, a fixed number of families are created. However, the immigration is driven by the village food production. The immigration stops when the production is not sufficient to meet the population food requirement.

5.6.2.2 The dynamics of the Herd entity

The animal dynamics in CaTMAS is represented through the pastoral dynamics (ingestion and excretion), the energy transformation, natality and mortality.

Ageing, birth and death

The herds ageing, birth and death evolve in the same manner than the family ageing, birth and death.

Grazing and excretion

Ingestion and excretion are seasonal. At each step of the simulation, the animals prospect the landscape for grazing. Ingestion stops when their food requirement is achieved or when the maximum duration of grazing is reached. Then, on each plot, forage intake and excretion of faeces and urine are computed according to biomass availability, plot length, staying time and hourly intake and excretion (faeces and urine).

The energy transformation

The animal mass increases according to the energy transformed from the food intake. Two models are used to define increase in the animal mass according to the intake (Breman and Ridder, 1991). The mass increases if the intake is greater than the energy requirement (Equation 5.1) else the mass decreases (Equation 5.2).

$$MG = ((DMint - DMreq) * MM * 17.6) * (18.1 * 1000) \tag{5.1}$$

$$ML = ((DMreq - DMint) * MM * 17.6) * (0.84 * 18.1 * 1000) \tag{5.2}$$

The following factors are used to compute the weigh growth in CaTMAS:

- WG: increase in the animal mass (kg),
- ML: decrease in the animal mass (kg),
- DMint: daily intake of digestible dry matter intake $gkg^{-0.75}$,
- DMreq: daily digestible dry matter requirement (in $gkg^{-0.75}$ of metabolic mass),
- MM: metabolic mass (in kg),
- energy contents (in MJ) of digestible dry matter, ($17.6MJkg^{-1}$),
- 0.5 is the share of digestible energy available for bodily need,
- 18.1 is the energy contents (in MJ) per 1 kg of animal,
- 0.84 factor determining the remain of the bodily energy after 16% of bodily energy used by the animal for its maintain if the food requirement is not meet.

5.7 Conclusion

This chapter illustrated the OREA model to complex system modelling. The C dynamics at the village scale is a complex system. According to Müller (2004), the description of the complex system minimally implies the articulation of the levels of the components, of the whole and of the underlying environment. The conceptual model of CaTMAS takes into account these different dimensions in the C dynamics description. This is made possible through the use of the MAS approach and the OREA model. The micro level concerns the entities level and the global level is defined through the organisations which constrain the entities behaviour.

The OREA application in the modelling of C dynamics showed that the OREA model provides framework to describe an entity from different points of view (internal and external points of view) by using the notions of aspect and role. That allows a flexible way to describe a system and makes the understanding of a conceptual model easer. In addition, it is possible to separate explicitly the organisation behaviour from the entity behaviour from the internal point of view.

From the methodological point of view, the OREA model allows to move from a problem to a conceptual model describing a system in different points of view. As noticed in Chapter 2, the CS modelling starts by a set of questions: what levels of description to choose, what variables to take into account? This step is crucial because it allows the modeller to define the scopes of the study that will guide her/hin in model building. Based on the identification of the scales of description and underlying dynamics, the OREA methodology allows defining what a model should include in order to provide a realistic representation of a CS. The first step of the OREA model corresponds to the third part of the Shannon methodology Shannon (1998). The other steps of the OREA methodology corresponds to fourth step of the Shannon's methodology (Conceptual model formulation). However, OREA methodology does not cover the implementation and the simulation steps. These steps in CaTMAS model building are presented at the chapter 6.

Chapter 6

Implementation of the CaTMAS model and simulation

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6.1 Introduction

Chapter 5 presents the conceptual framework of the CaTMAS model defined through the OREA meta-model. A simulator has been implemented using this conceptual framework. This current chapter aims at presenting this simulator. CaTMAS is based on the MAS approach, and coupling with the Century model and a Geographic Information System (GIS). This model has been implemented as an integrated model providing a framework to represent the interactions between humans and the environment in carbon dynamics framework. The model takes into account the heterogeneity of farming systems, the humans activities impact on carbon dynamics and the environmental feedback. It allows assessing the carbon dynamics under several socio-economic and bio-physical scenarios. In order to test the simulator, a virtual village has been specified by using data from the literature. The CaTMAS model was run to simulate the impacts of the climate change and the population growth on the dynamics of C resources and the vulnerability of two contrasted farming system.

This chapter presents firstly the implementation, the description of the parameters, the input data from the literature and the scenarios built for the simulation. Then, we discuss some simulation results. The third part presents a discussion about CaTMAS and some possible development for its extensions.

6.2 Material and method

In addition to analysis and definition of a conceptual model, a simulator building includes the model implementation, the definition of the types of parameter and experimentations through a set of scenarios (cf. section 2.4 page 17). This section aims at presenting:

- the implementation of CaTMAS with its coupling with Century and GIS,
- the description of the types of parameters for a village description from social and bio-physical point of view,
- the imput data and scenarios used for experimentations

6.2.1 Implementation of CaTMAS

The CaTMAS has been implemented in order to include the interactions between the demographic dynamics, the land-use change, the pastoral dynamics and the bio-physical processes (Fig.6.1):

Demographic dynamics : the demographic dynamics are represented through natality, mortality, immigration and emigration.

Land-use change : represents the farmers' production activities through crop and animal production. The land-use includes the farmers' decision rules, their objectives, OM management, cropping system, etc.

Pastoral dynamics : represents the animal production and their activities through intake, excretion. The production includes the cycle of animals production: birth, growth, ageing, death and selling.

Bio-physical process : represents the interactions between plant, soil and climate. The bio-physical properties are indicators of the viability of a farming system . They influence farmers' decision rules and crop production. The bio-physical processes influence also the demography. In our model, the natality/mortality, immigration/emigrate rates evolves according to the food production which depends on soil properties.

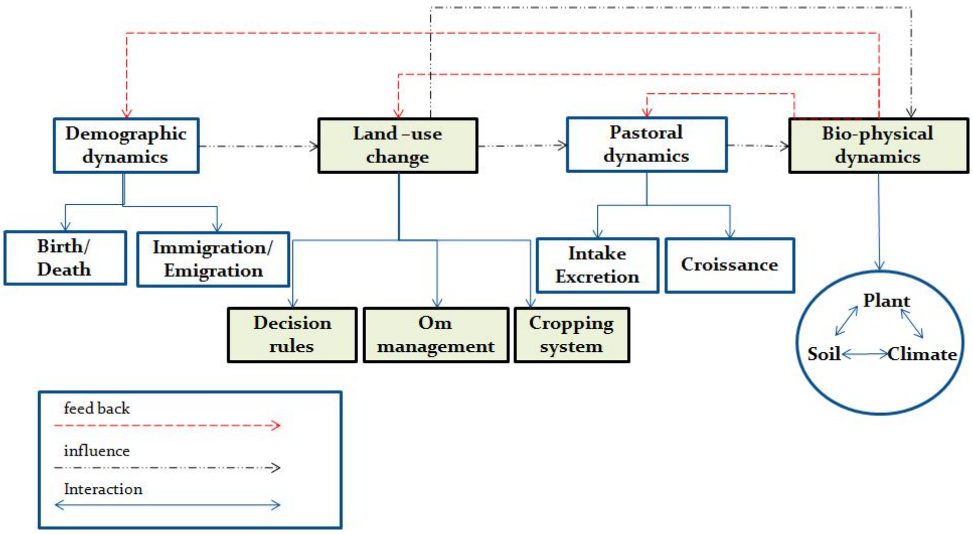

Figure 6.1: Representation of farming system in the CaTMAS model

6.2.1.1 The architecture of the CaTMAS model

The architecture of the CaTMAS provides 4 modules (Fig. 6.2). The first module provides the conceptual framework. It concerns the kernel of our model. It is composed of the Mimosa model, the OREA meta-model (cf. chapter 4 page 55) and the CaTMAS conceptual model (cf. chapter 5 page 83). The second module "coupling module" manages the coupling between CaTMAS, Century and GIS. To allow the communication between Century and CaTMAS, a TCP/IP communication is used. The communication is managed by the third module: "Network module". The last module "data module" manages the input and the output of the simulation. It provides data to the first and the second module. The "data module" uses Postgresql[2]and Postgis[3]. The input data are managed through a parameter manager. The parameter manager provides the description of a village (cf. section 6.2.2 page 124).

images/CatMas/architectureCatMAS.JPG

Figure 6.2: Architecture of the CaTMAS model with its different modules

The different modules have been implemented through the following Java[4] packages:

`mimosa.catmas.entities` implements the different entities of the model (*Family*, *Herd*, *VillageTerritory*, etc.). Each entity is implemented by a Java class. In addition to the entities identified, the package implements two main classes describing the model: `CatMas` and `CatMasDescription`. The `CatMasDescription` class derives from `ModelDescription` of the OREA meta-model (cf. section 4.4 page 68). It provides the description of the CaTMAS structure. The `CatMas` class derives from the `Model` class of the OREA meta-model; it represents the concrete model (cf. section 4.4 page 68). In addition, it initializes the model and manages the parameters and coupling with Century and GIS (Fig.6.3). The Appendix **??** provides the description of the database.

`mimosa.catmas.organisations` implements the organisational structure of the model (groups, roles and competences). The groups, roles and competences have been implemented as first class entities.

`mimosa.catmas.parameters` package implements the parameters of the model. These parameters provide a description of village territory from the user point of view as defined in section 6.2.2 (page 124).

`mimosa.catmas.century` package implements the classes managing the coupling with Century and the database. Three classes have been implemented:`CenturyConnection`, `ThreadingCentury` and `DataBaseConnection` classes. The `CenturyConnection` class manages the coupling with Century model through the `ThreadingCentury` class. This last class inherits from the Java `Thread` class and allows a parallel simulation of the plots. The coupling with database is implemented by the `DataBaseConnection` class. The parameters for the database connexion are defined by the user in a file (cf. section 6.2.1.2 page 121). This file is read by the `DataBaseConnection` to link the model to the database using jdbc.

`mimosa.catmas.gis` manages the coupling with the GIS. Several classes implement the coupling with the GIS. The `SpaceModel` class implements the map. It is characterized by a set of

[2]http://www.postgresql.org/
[3]http://www.postgis.fr/
[4]http://java.sun.com/

cells implemented by the `GisCell` class. This class implements the relation between an entity (e.g. **Plot** entity of CaTMAS) and a cell and updates the GIS data in database according to the state of the entity. A `GisCell` is characterized by a set of located entities. These entities are implemented by the `SpatialEntity` class. It defines the location of entities (e.g. *Herd* and *Family*) in the space. This package is generic and can be used for other models.

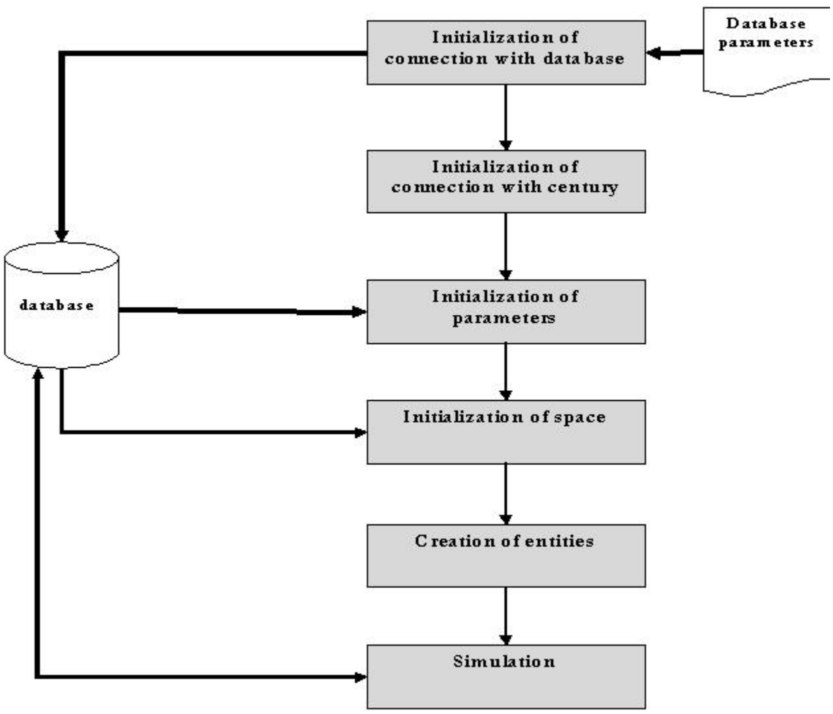

Figure 6.3: Simulation with the CaTMAS model

6.2.1.2 Coupling with Century

The version 5.0 of Century[5] has been implemented in the object-oriented programming language C++[6]. Initially, Century has been developed to simulate carbon dynamics for one type of soil under a management scheme and a climate regime that must be specified before the simulation. Century is a deterministic model. It does not allow for inclusion of unpredictable/stochastic events. The time patterns of entity variables at one site must be defined before the simulation. CaTMAS is a MAS model implemented in the Java language. In addition, the environment of the CaTMAS model is composed of numerous plots (few hundreds to several thousands). Each plot is characterized by one type of soil and one vegetation cover (tree, crop, grass, mix of a

[5] http://www.nrel.colostate.edu/projects/century5/
[6] http://www.cplusplus.com/

tree-grass or tree-crop). A framework is thus needed to allow (1) interactions between Century and CaTMAS and (2) multiple-site simulations.

For that, CaTMAS has been implemented to run in a network context. A simulation is distributed between several computers. The model is composed of two parts: the MAS model which simulates the entities dynamics and the Century model which simulates the soil C and plant of each plot. The first part runs on a workstation while the second part can be distributed among several computers running as servers and workstation. The servers and the workstation exchange data through a database. The database contains the description of all types of soil (land cover, physical and chemical properties) and the management events of all plots and the output. However, the database server is installed on one computer and the other computers use the same database for the input and output of the simulation.

The plot simulation is a process of interactions between the workstation and the servers (Fig. 6.4). To simulate a plot, the Client (CaTMAS) sends a message to the Server. This message is a Century command line and contains the identity of the plot to simulate. When the server receives the message, it creates the Century input files. The input data are read from the database. After, the input creation, the server runs Century. The output of the Century is read from the century output files to be written in the database and used to update the plot data in CaTMAS. The output of each plot is also used as the initial state of the plot for the next simulation with Century.

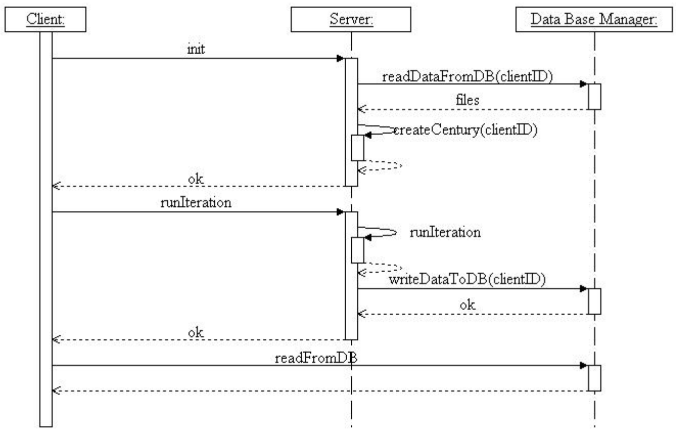

Figure 6.4: Description of Century-CatMAS coupling with the sequences diagram of UML

The management scheme of a plot is defined using the events that occurred on the plot during the last twelve months. Then, all events (crop planting, tree removal, burning, grazing, fertilization, harvest, etc.) that occurred on a plot are saved in the database on a monthly basis.

To allow the communications between workstation, servers and the database access, The user must define in files the data for the database connexion and the servers and workstation addresses.

(Fig.6.5 and Fig.6.6). The parameters for the database connexion concern the database name, login (user name and the password), database server, port of connexion and the simulation name (for the input and output files creation).

```
#Parameters of the database connexion

#dbname user pwd server dbport simulationName

CatMas root  catmas  127.0.0.1 5432 simulation

#Address(es) of Century servers

127.0.0.1 147.99.15.66
```

Figure 6.5: Example of parameters for a local access to database and servers in the workstation inside

```
#Parameters of the database connexion

#dbname user pwd server dbport simulationName

CatMas root  catmas  127.0.0.1 5432 simulation
```

Figure 6.6: Example of parameters for a local access to database in a server inside

6.2.1.3 Coupling with GIS

The coupling of CaTMAS with the GIS is based on a dynamic coupling using PostGIS (Fig.6.7). The environment is represented as a grid of regular cells (1 ha). Each cell defines a plot and is characterized by a type of soil and a type of vegetation cover. In the CaTMAS model, each GIS cell is represented by a dynamic entity: the **Plot** entity playing the role of interface between GIS and the CaTMAS model.

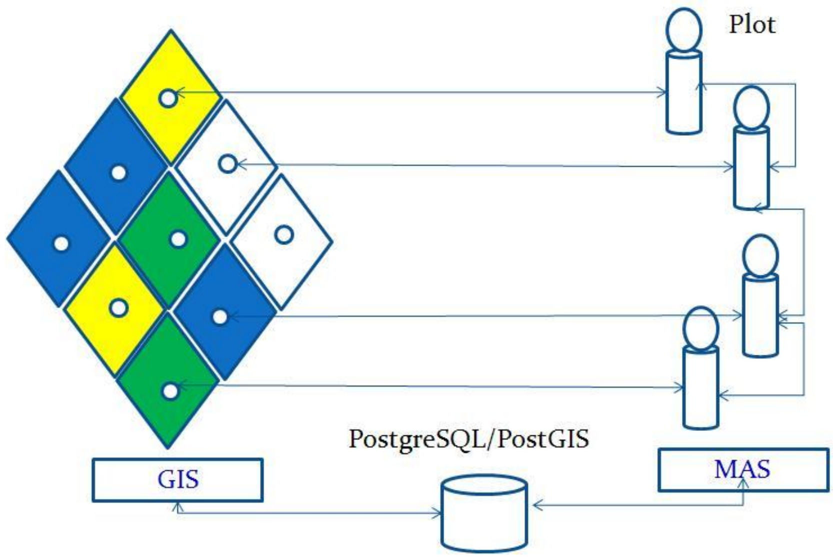

Figure 6.7: Gis-CatMas coupling

6.2.1.4 Time management

The CaTMAS model can be used on a daily or monthly increment depending on the objectives of the simulation and the size of the simulated site. The daily simulation is time -computer resources- consuming. The various entities in the model do not all evolve at the same scale of time: the Herd entities can also evolves on a daily and monthly basis. The *Family* and *Climate* entities evolve on a monthly basis.

6.2.2 The description of the parameters

For a realistic representation of a village territory and to increase the genericity of the CaTMAS model, a conceptual framework has been proposed to allow the users of the simulator to describe a village territory by taking into account its social and environmental diversity (Fig 6.8). From methodologically point of view, this description can be viewed as method for the definition of typology of cropping systems with CaTMAS.From the simulation point of view, this conceptual model provides an explicit description of the CaTMAS types of parameter.

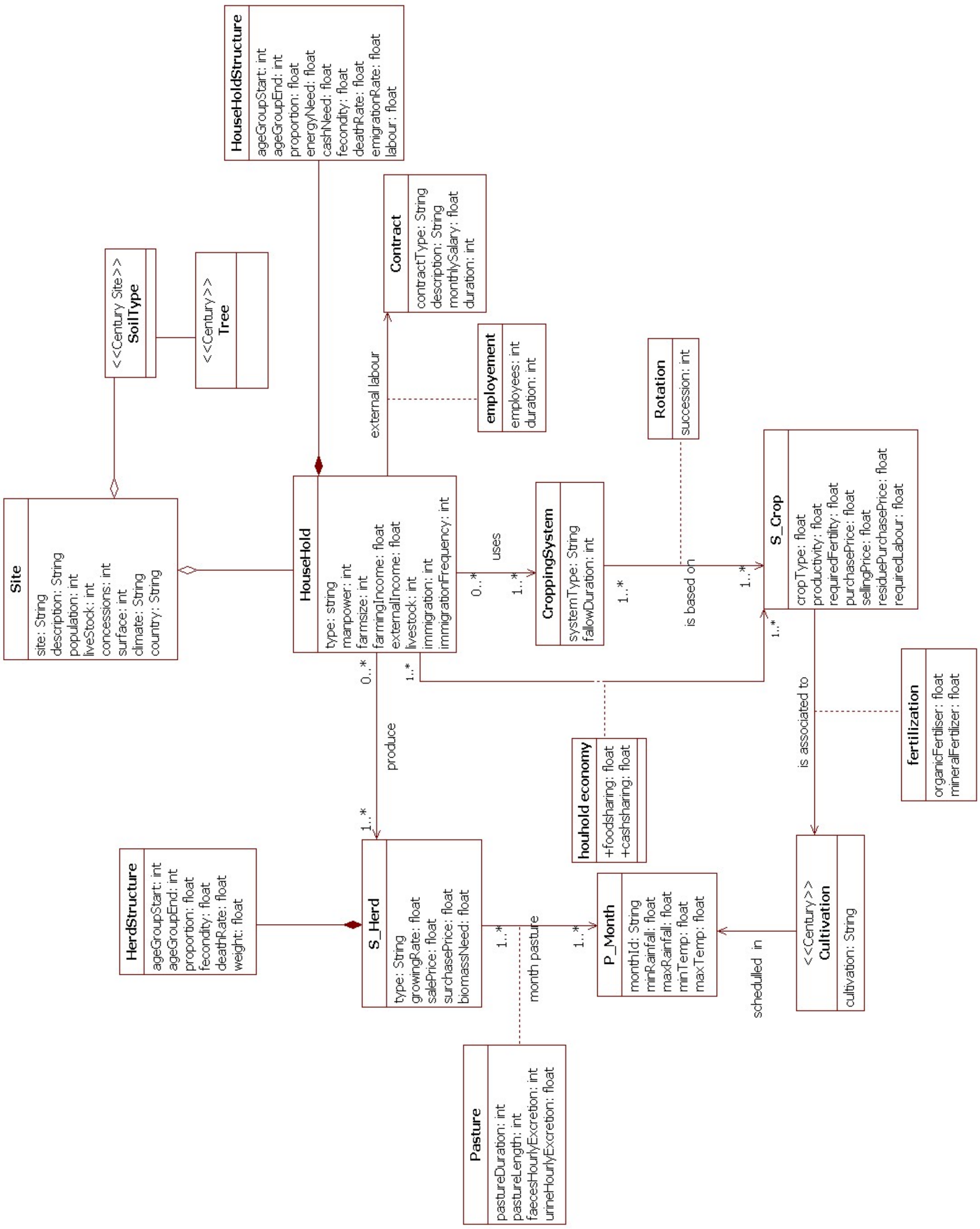

Figure 6.8: UML diagram class of CaTMAS model paramters

6.2.2.1 The social description

The social organisation in CaTMAS is composed of various types of families. Each type of family (*HouseHold* class in Fig.6.8) describes the families which share the similar features with regard to population, activities, land-use decision, food security strategies, etc. To describe a type of family, the following variables have been identified: proportion of the types of family in the village community, family initial population size (number of persons), farm size, labour, initial amount of cash, distribution of the population into classes, activities (cropping and animal production), mobility (emigration and immigration) and food security strategies.

Family structure

The family structure defines the distribution of humans into age classes (*Householdstructure* in Fig.6.8). Each age class is characterized by its relative contribution in the total population of the family, mortality rate, emigration rate, energy and money needs and labour capacity.

Activities description

Two activities are described: crop production and animal production.

Crop production

The crop production is defined through the cropping systems (*CroppingSystem* class in Fig.6.8). A family can use several cropping systems. A cropping system is defined by crops rotation (*Rotation*) and the fallow duration. For each type of crop (*SCrop*), labour requirement and farming calendar (*FarmingCalendar*) have been defined. *FarmingCalendar* describes the cultivation operations (planting, weeding, fertilization, harvest, etc.) to schedule each month.

Animal production

Several types of animals (sheep, goat, cattle) can be represented (*Herd* class). Each type of animal is characterized by its structure (*HerdStructure* class) and pastoral value (*Pasture*) according to the seasons (grazing, excretion, pasture length). The structure of the herds consists of the population distribution into age classes. Each age class is characterized by its relative contribution to the herd size, initial weight and mortality and selling rates.

Emigration and immigration

Emigration is a function of the individuals age class; it is defined by the emigration rate of the age class. Immigration depends on the family type. For each type of family, two variables (*immigration* and *immigrationFrequency*) have been defined to specify the arrival in the village. *Immigration* is the number of new households created at each period (*immigrationFrequency*).

The families economy

According to the family type, the share of each crop for the food need and cash needs requirement is defined (*HouseHoldEconomy*). This specification is used to define the plans of production and selling according to the families' objectives. The plan of production defines the area to cultivate for each crop while the plan of selling defines the quantity of each crop to sell and stock in order to meet the food and cash needs.

6.2.2.2 The description of the environment

The environment is defined through the types of soil, vegetation (woody, herbeceous) and their spatial distribution. A type of soil description takes into account the biological, physical and chemical properties. Soils and vegetation are defined using the Century model site description.

6.2.3 The input

We defined a set of data to specify a virtual village for experimentations with CaTMAS. The input data used derived from several literature sources and the Century model. The input data concern the demography, the cropping systems, the households' economy, the bio-physical properties of a village (types of soil, climate data, etc.), the properties of animals (the herd structure, pastoral values, etc.) and the GIS data.

6.2.3.1 Cropping systems and crops

The cropping systems used for the simulations derived from the Touroukoro cropping systems (Youl, 2009) (Table. 6.1). Two cropping systems are used: the semi-continuous (SCS) and continuous (CS) systems. The SCS is based on fallowing and the 5 years yam-maize-sorghum-sorghum-sorghum rotation. The fertilization in SCS is organic. The CS is based on fallowing and 5 years maize-cotton-maize-sorghum-sorghum rotation. The farming calendar associated to the cropping systems is derived from (Matlon and Fatchamps, 1988). Sources from literature have been used to describe the crops properties (Table 6.2): the energetic value, the labour (Matlon and Fatchamps, 1988), the purchase price and the selling price (Youl, 2009).

6.2.3.2 Demography

The social organisation is based on two types of households corresponding to the description of two types of households in Touroukoro (Table. 6.3) (Youl, 2009): autochtone using the SCS

Table 6.1: Crops succession in the two cropping systems simulated

Cropping system	year	crop
Semi-continuous (SCS)	1	yam
	2	maize.
	3	sorghum
	4	sorghum
	5	sorghum
Continuous (CS)	1	maize
	2	cotton.
	3	corn
	4	sorghum
	5	sorghum

Table 6.2: The description of crops used in the simulations

crops	labour (men-days)	energetic value kCal g^{-100})	Purchase price (€t^{-1})	selling price (€t^{-1})
maize	102	327	110	110
sorghum	65	371	133	133
yam	265	112	154	154
cotton	139			236

cropping system (H1) and migrant (H2) using the CS cropping system. The properties of the household have been changed for the simulations. The demographic data were derived from Burkina Faso values (household structure, natality, mortality). This data has been defined using UNPP database (UNPP, 2006, 2005). We used the FAO data (FAO, 2001) to define the human energy requirements according to the age group. Using this data, the households' structure has been defined (Table 6.4).

Table 6.3: The description the household types simulated and means of production

household type	size	farm size	livestock	employees	cropping system
H1	20	31	26	5	SCS
H2	20	15	38	5	CS

The households' economy and food consumption depend on the cropping systems (Table 6.5). Then, the H1 households food (energy) consumption is distributed between on maize (60%), sorghum (20%) and yam (20%) and their cash flow comes from maize (10%), sorghum (10%) and yam (80%). As to H2 households, their food consumption is based on maize (80%) and sorghum (20%), and the cash need is based on maize (20%), cotton (70%) and sorghum (10%).

Table 6.4: Fixed features of the human population of household used for the simulation

Age group		Proportion	Fecundity	Mortality	labour	Energy need	Money need
Start	end	(%)	(%)	(%)		(Kcal day^{-1})	(€year^{-1})
0	4	18	0	0	0.00	1290	45
5	9	15	0.00	0.00	0.00	1920	45
10	14	12	0.00	0.00	0.45	2450	45
15	19	10	13	0.00	0.45	2630	45
20	24	9	43	0.00	0.95	2388	45
25	29	7	33	0.00	0.95	2388	45
30	34	6	17	0.00	0.95	2310	45
35	39	4	7.5	0.00	0.95	2310	45
40	44	3	2.3	0.00	0.95	2240	45
45	49	2	0.8	0.00	0.95	2240	45
50	54	2	0.00	0.00	0.95	2060	45
55	59	1	0.00	0.00	0.95	2060	45
60	64	1	0.00	0.00	0.95	1885	45
65	69	1	0.00	0.00	0.95	1885	45
70	74	0.7	0.00	0.00	0.95	1645	45
75	100	0.12	0.00	0.00	0.95	1645	45
101	1000	0.00	0.00	1	0.00	1645	45

Table 6.5: The crop sharing for the cash and food requirements

household type	crop	selling (%)	feeding (%)
	maize	10	60
H1	sorghum	10	20
w	yam	80	20
	maize	20	80
H2	cotton	70	0
	sorghum	10	20

6.2.3.3 Biological and physical data

Biological and physical (e.g. soil texture, SOM, land cover) properties have been defined using the data from several studies in West Africa (Manlay et al., 2002, 2004a,b, Youl, 2009). In the current simulations, we assume that all the plots have the same properties. The initialisation of the environment is not realistic, but it allows comparing the impacts of various organic matter management strategies and cropping systems. The vegetation is composed of tropical shrub and C4 grass of Century.

6.2.3.4 Animal data

The data of animals concern the structure of the herds and their activities (grazing and excretion). Only cattle has been simulated. The herd structure (Table 6.6) used for the simulations was derived from (Breman and Ridder, 1991). But this data has been adapted in order to take into account all age classes. As for pastoral activities (intake, excretion, grazing length and duration) (Table 6.7), the data from (Botoni, 2003, Hoffmann et al., 2001, Landais and Guérin, 1993, Schlecht et al., 2006) were used.

Table 6.6: Fixed features of the animal population used for the simulation

Age group		Proportion	Live weight	Mortality rate	Selling rate	Calving
Start	end	(%)	(kg)	(%)	(%)	(%)
0	1	10	20	43	0	0
1	2	10	100	5	0	0
2	3	12	150	5	0	0
3	4	12	150	5	0	36
4	5	12	150	8	0	47
5	6	11	250	8	0	57
6	7	8	250	8	0	57
7	8	6	250	8	0	57
8	9	5	250	8	0	57
9	10	5	250	8	0	57
10	11	4	250	8	23	50
11	12	3	250	8	46	50
12	13	2	250	8	69	50
13	...	1	250	8	92	50

Table 6.7: The pastoral values of the Cattle

Month	Grazing length km day^{-1}	Biomass intake (t DM TLU^{-1} day^{-1})	Faecal excretion (t DM TLU^{-1} day^{-1})
January	13	0.0063	1.325
February	13	0.0063	1.30
March	13	0.0063	1.35
April	11	0.0063	1.16
May	11	0.0063	1.10
June	11	0.0063	1.05
July	13	0.0063	1.25
August	13	0.0063	1.25
September	13	0.0063	1.25
October	14	0.0063	1.25
November	14	0.0063	1.45
December	14	0.0063	1.98

6.2.3.5 Climate

The climatic data are based on the precipitation and temperature pattern of Bobo-Dioulasso (Burkina Faso) of the year 2006, provided by the Burkina Faso department of meteorology (Table 6.8).

Table 6.8: The temperature and rainfall of Bobo-Dioulasso

Months	Rainfall	Temperature (°C)	
	(mm)	Min	Max
January	0	19.8	34.2
February	0.0	22.4	36.2
March	0.1	24.8	38.4
April	23.8	25.7	37.5
May	140.2	23.7	34.9
June	154.1	23.7	34.9
July	115.9	22.0	34.4
August	249.9	21.5	30.5
September	276.4	20.9	30.7
October	144.6	20.9	30.7
November	0.0	20.9	34.1
December	0.0	18.5	32.5

6.2.3.6 The spatial data

The GIS data for Touroukoro were used for the spatial representation of the environment. The space has been decomposed into plots (1 ha). From this GIS dataset, only an area of 530 plots was simulated. Two spatial layers have been defined: the land-use layer and the C layer.

6.2.4 The scenarios

Several scenarios have been defined. These scenarios take into account the social organization and the climate and economic factors.

6.2.4.1 The social organization

The population is composed initially of 20 households: 10 of H1 type and 10 of H2 type. We do not take into account the immigration in the current simulation. We assume that all household types have initially the same structure.

6.2.4.2 The climate scenarios

The climate scenarios are based on the variation of the mean monthly temperature and the annual precipitation. Three climate scenarios are used: C1, C2 and C3. Scenario C1 is based on the actual precipitation and temperature. The last two are the future climate scenarios as defined in (Lufafa et al., 2008). C2 scenario is a 1.5°C increase in mean monthly temperature and a 25 mm decline in annual precipitation. The C3 is a 3°C increase in mean monthly temperature and a 50 mm decline in annual precipitation.

6.2.4.3 The economic scenarios

Two economic scenarios are combined to the C1 climate scenario in order to analyse the economic impacts: E1 and the E2 scenarios. E1 is based on the individual cash need defined in Table 6.4. E2 consists in a 50% increase in the individual cash need. The objective of the E2 is to simulate the future increase in the individuals income.

6.3 The results

6.3.1 Impact of climate change on land-use and C dynamics

The population growth impacts considerably the land-use. When, the population grows, the cultivated land increases and the forest and the land under fallow decrease. In C1, the fallowing increases during the 10 first years and decreases after while the forest decreases and the cultivated land increase (Fig.6.9 and Fig.6.10). Similar trends are observed in the C2 and C3 scenarios (Fig.B.1 and Fig.B.2).

We observe that the land cultivated per capital in C3 is higher than in C2 and C1 (Fig.6.11). But this trend is visible almost 30 years of simulation only. But, the population growth is low in C3 than in C1 and C2 (Fig.6.12).

The high-level of the cultivated land per person in C3 could be a consequence of low grain yield, pushing the farmers to increase the area cultivated to meet their needs. The Century model computes the grain production according to the biomass production which depends on temperature and rainfall. In CaTMAS, farmers take into account the previous crops yields to define their cropping plan. When the crop yield decreases, the farmers increase the cultivated land the year after. Then, in C1 scenario where the crop production is the highest, the cultivated land is the lowest and the SOC the highest in comparison to the SOC in C2 and C3 scenarios. The high-level of the SOC in C1 allows a better grains yield. That could explain the highest

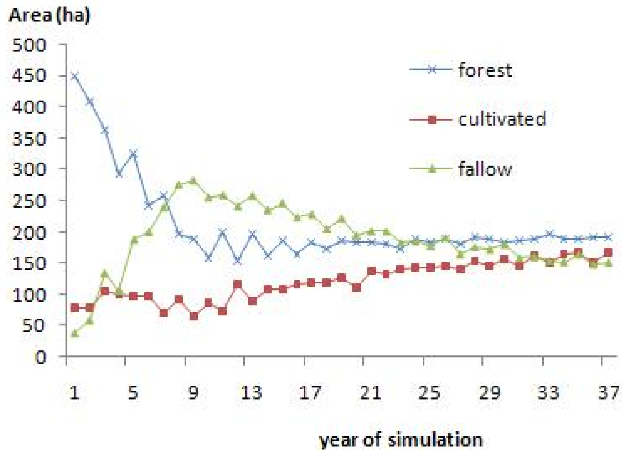

Figure 6.9: Simulated evolution of the land use extension in the C1 scenario

population growth in C1 scenario and the lowest population growth rate in C3 scenario.

The simulations show that the SCS allows a higher density of soil organic carbon than in the CS (Fig.6.13, Fig.6.14 and Fig.6.15). After 35 years of simulation, the SOC in CS is 26% lower than in SCS, and 25% and 23% respectively in C2 and C3 . Climate change has an important impact on the C sequestration in SCS.

After 35 years of simulation, the SOC density in SCS falls by 3, 10 and 17% in C1, C2 and C3 respectively. In CS, the SOC falls by 29, 33 and 36% in C1, C2 and C3 respectively during the same period. In the three climate scenarios, the fallowing length in SCS ranges 1-15 years while it ranges 1-5 years in the CS (Fig.6.16). Then, the crop intensity in permanent system is higher than in semi-permanent system. The higher storage in SCS could be due to the fact that the fertility management is based on organic matter and the fallowing length is higher than in CS. Not using the organic fertilizer, the SOC reduction in CS is very important. The analysis of the spatial distribution of SOC density shows the impact of the two cropping system and climate change on the C dynamics (Fig.6.17, Fig.B.8 and Fig.B.9).

From the economic point of view, climate change impacts the cash production. Cash production per capital in C3 is lower than in C1 and C2 (Fig.6.18). The low level of cash production in C3 could be due to the low crop production. In CaTMAS, the farmers' cash depends on the crops production. After the harvest, the farmers store the production that they need to achieve the energy need and the remainder is sold.

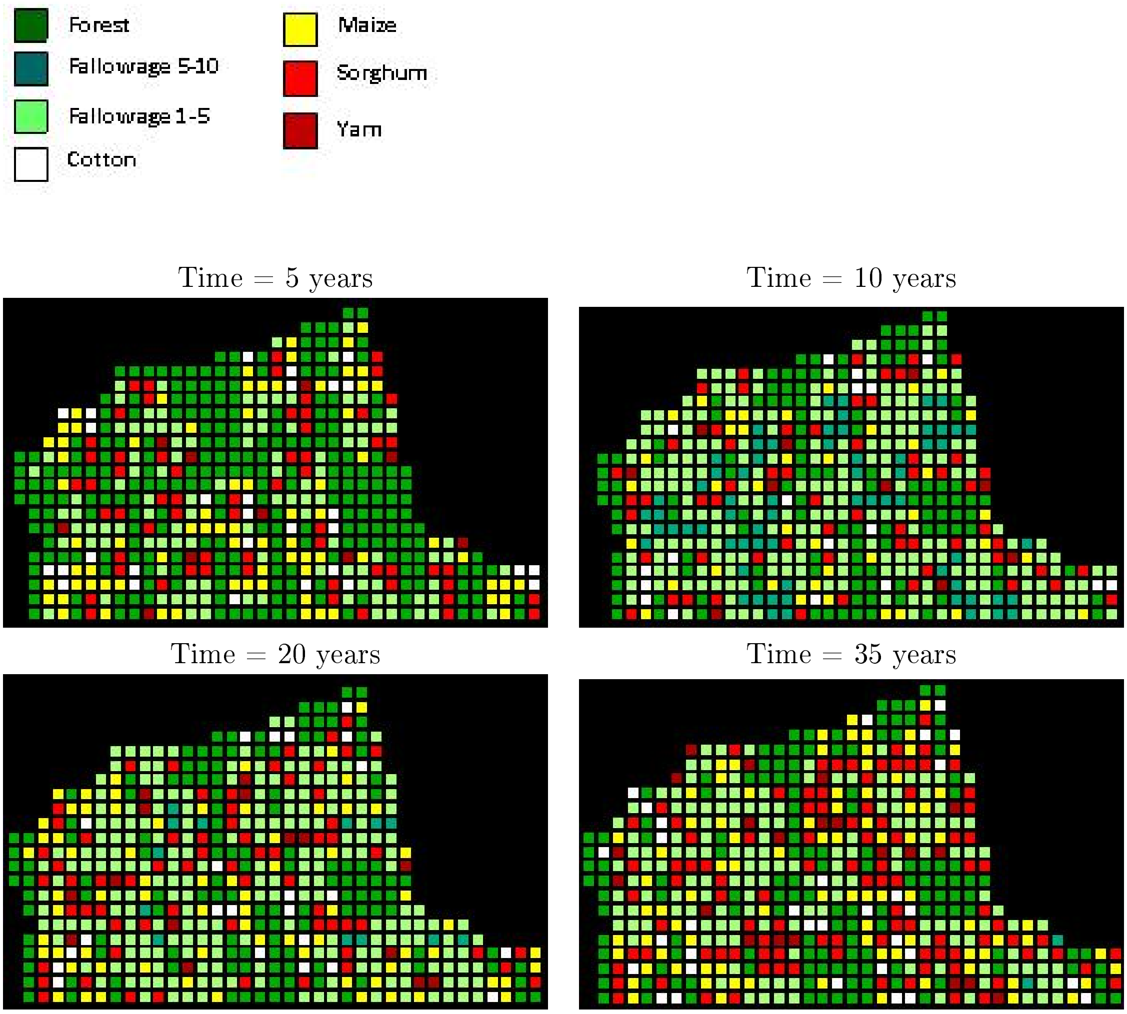

Figure 6.10: Evolution of the land use spatial distribution under the climate scenario C1

6.3.2 The impact of economic change on C dynamics

6.3.3 Impact of carbon dynamics and population growth on animal husbandry activities

The pastoral output concern the pastoral length, the number of TLU in the village and the live mass of the animals. Climate change impacts the pastoral activities. The daily length of animals' trajectories in C3 is higher than in C1 beyond seven years of simulation (Fig.6.19).

The increase in the pastoral length in C3 should be due to the decrease in the plant biomass production and availability. In CaTMAS, forage intake and excretion of faeces and urine are computed according to biomass availability, plot length, staying time and hourly intake and excretion. Then, the pastoral length increases inversely with the biomass production.

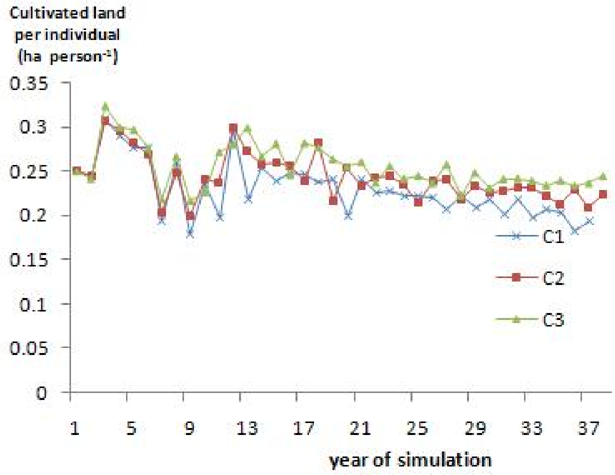

Figure 6.11: Simulated impact of climate change on the evolution of the land cultivated per capital

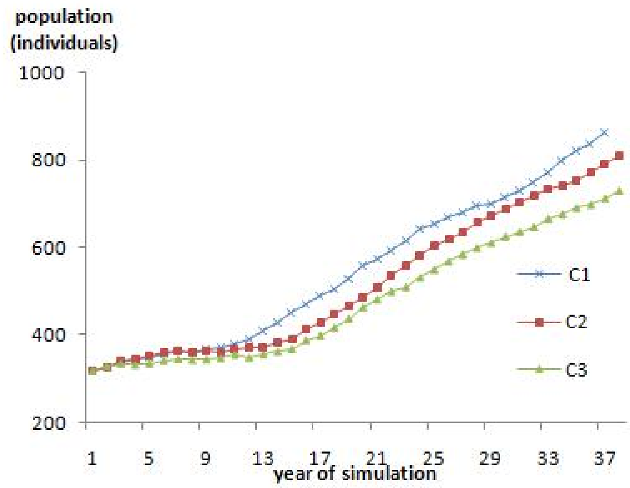

Figure 6.12: Simulated impact of the climate change on the population size

The impacts of the biomass production on the pastoral activities are shown in the Fig.6.20. We observed two periods in the evolution in the animals mass. During the first period (1-15 years), the mass of the animals increases. It then decreases with the decrease being higher in C3 than in C1. The decrease in the mass after the 15th years should be due to the increase in the cultivated land. The increase in the land cultivated leads to decreased pastoral area and thus decreased availability of biomass on which the growth of the animals depends. The livestock evolution of the territory (number of TLU) and the density of the animals (TLU ha^{-1}) shows the response of the animal growth to the climate change (Fig.6.21 and Fig.6.22).

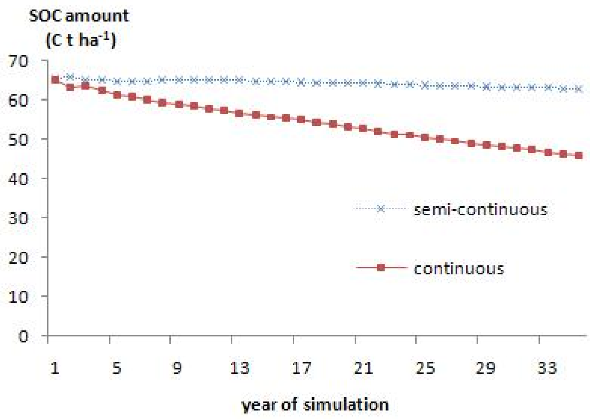

Figure 6.13: Simulated impact of the climate change on the C sequestration in SCS and the CS in C1 scenario

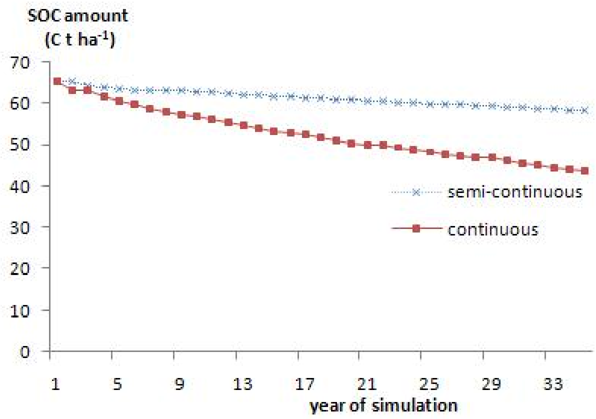

Figure 6.14: Simulated impact of the climate change on the C sequestration in SCS and the CS in C2 scenario

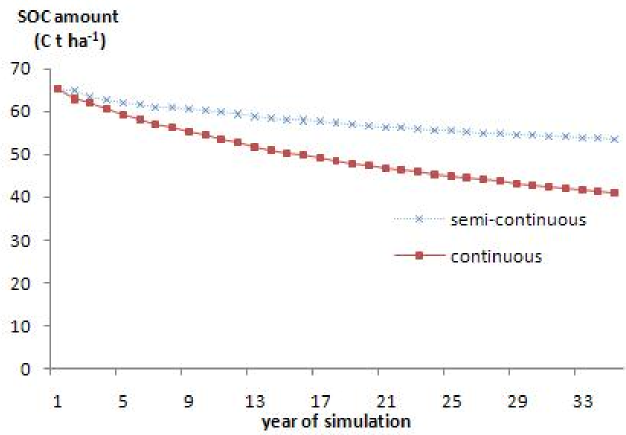

Figure 6.15: Simulated impact of the climate change on the C sequestration in SCS and the CS in C3 scenario

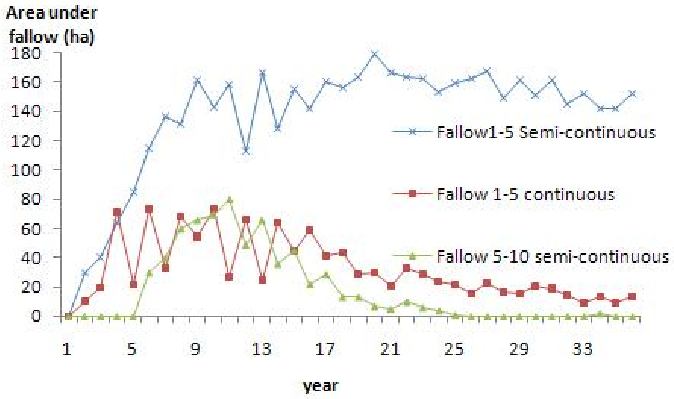

Figure 6.16: Simulated evolution in SCS and CS of the extension of fallowing by class of fallow duration in C1 scenario

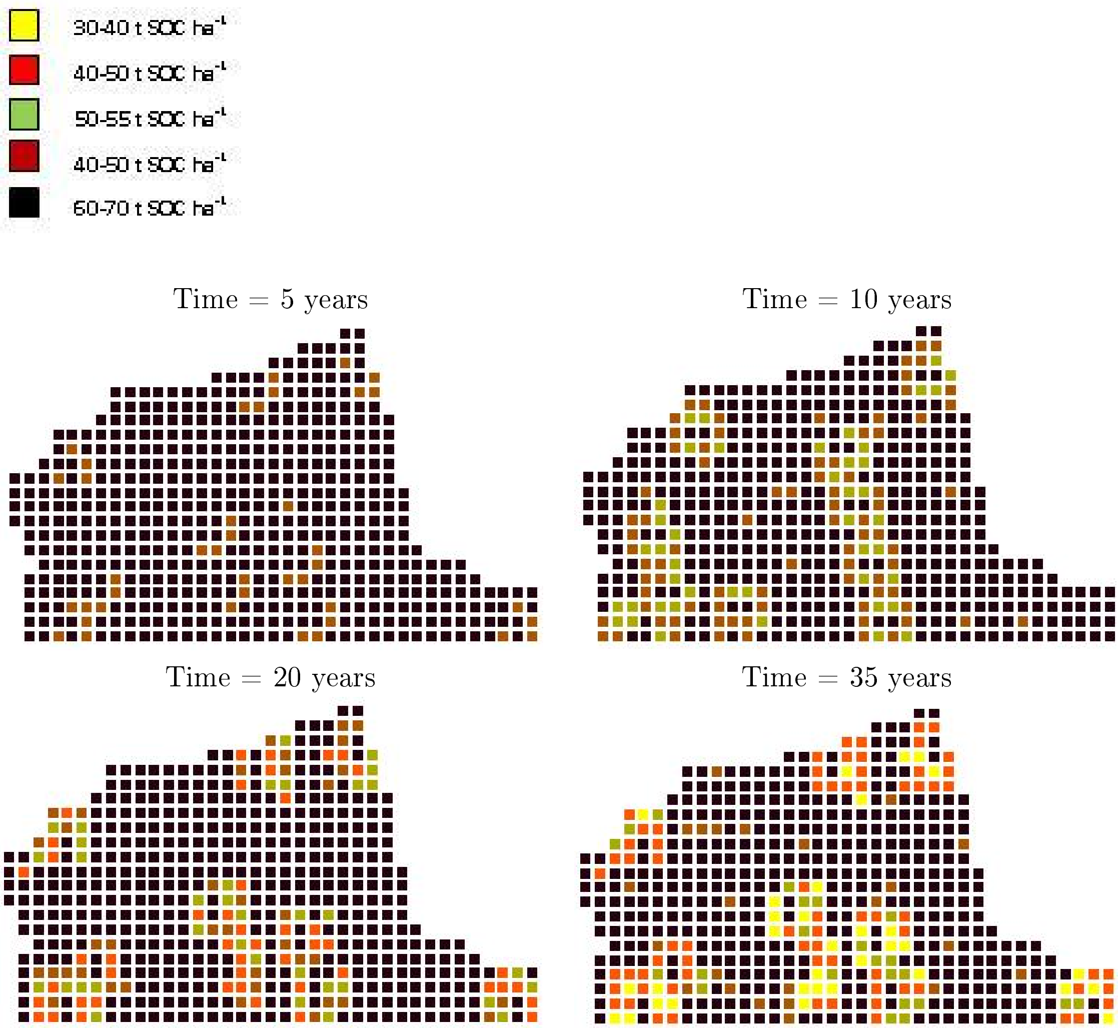

Figure 6.17: Simulated evolution of SOC spatial distribution in scenario C1

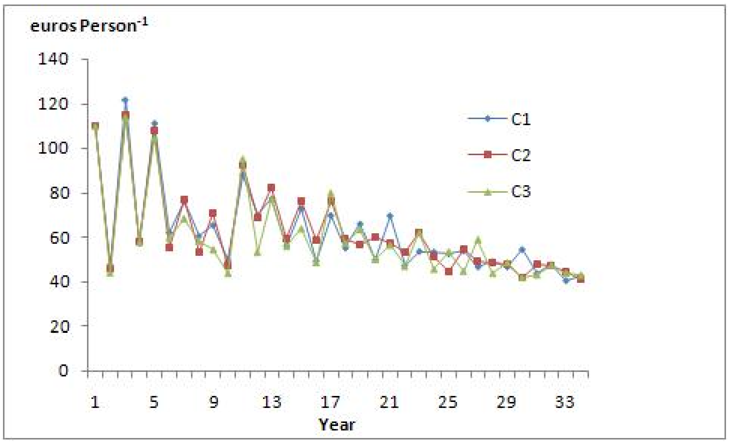

Figure 6.18: The cash production response to the climate change

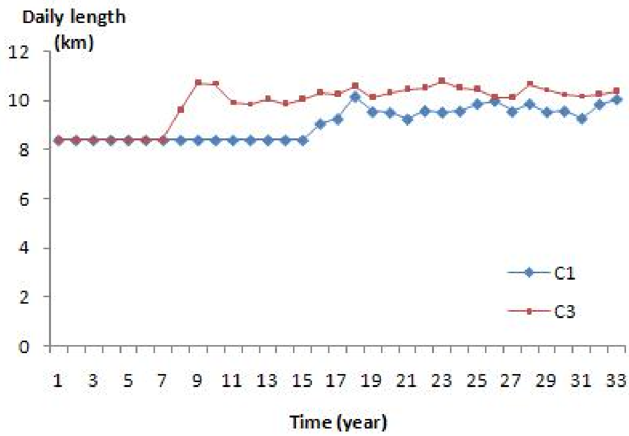

Figure 6.19: The impacts of the climate change on the daily length of herd trajectories under two climatic scenarios

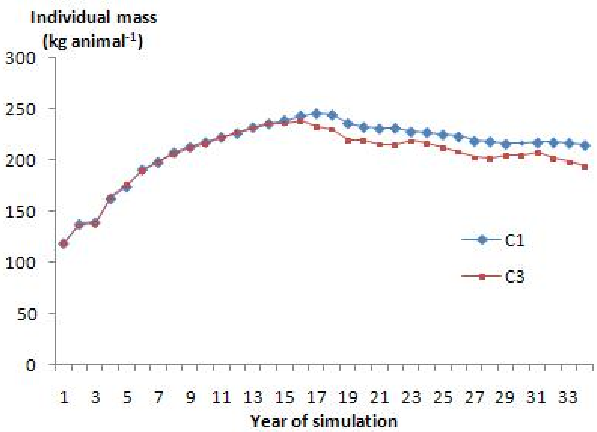

Figure 6.20: The response of animal live mass to the climate change

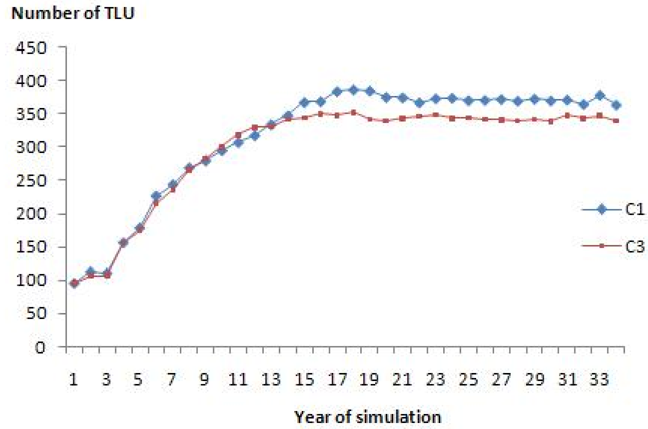

Figure 6.21: The evolution of the livestock in the response to the climate change

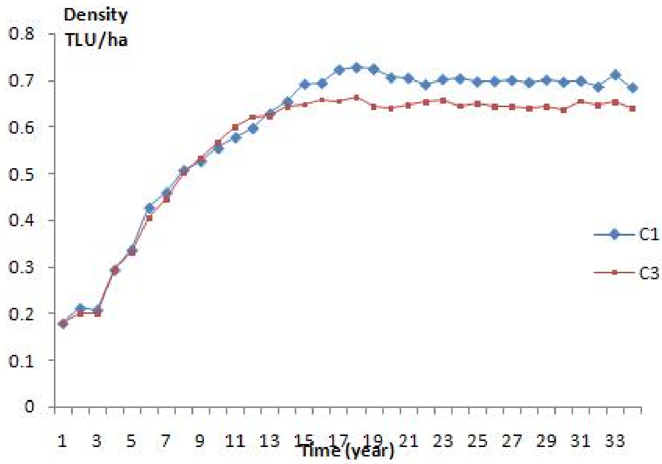

Figure 6.22: The density of the animals in the scenarios C1 and C3

6.4 Discussion

6.4.1 Relations between human and environment

The simulations showed that the CaTMAS model could account the relationships between population and the resources. When population grows, the cultivated area increases while SOC, fallowing length and forest area decrease. In addition, simulations showed that the population growth depends on the availability of C resources which influence the crop production. The SOC controls the soil fertility and thus the crop production. The population growth response to the C resources diminution can be viewed as an environmental feedback. The CaTMAS is a Malthusian model (Malthus, 1798). The decrease in C resources has not an important effect on the farmers' strategies. Apart from the increase in the cultivated land, farmers do not change their strategies to improve C management. Contrary to the Malthus approach, the Boserus approach

(Boserup, 1965) assumes that the stakeholders adapt their strategies if the resources decrease under a threshold in order to allow the regeneration of the resources. To take into account this hypothesis, it would be necessary to introduce an adaptive behaviour and the technology diffusion in the CaTMAS model. In addition, it would be necessary to study how the farmers react to the introduction of the new technologies in the system. This last point underlines the necessity to take into account the politic factors in the C dynamics. Then, it would possible to analyse (1) how the politic factors influence the C dynamics and the farmers' strategies and (2) the economic potential of the C sequestration.

6.4.2 Articulations between micro and macro processes

A complex system exists at different scales. The individuals in the complex system interact among them at different spatio-temporal scales. The individuals are embedded in an environment. They modify individually their environment but the effect on the environment change is collective. According to An et al. (2005):

> *"The accumulated impact of individual decisions made by dozens, hundreds, or millions of people is the immediate cause of human-induced environmental change. On the other hand, these individual actions are shaped by the particular social, political, economic, and environmental frameworks within which they occur. These frameworks change through time as conditions change. Furthermore, the imprint of these activities varies throughout space and across different spatial scales."*

Using Mimosa (an event-based model), CaTMAS represents the C dynamics at three time scales: day, month and year. From the spatial point of view, the C dynamics is represented at plot, farm and village levels. In addition, the model tackles the articulations between global and local dynamics in C dynamics and the environmental feedbacks on the individuals behaviour. The entities behave individually but the overall entities decision making impact the entities individually. The families in CaTMAS produce individually but their individual production impacts the global population growth rate. In addition, the animal individual intake impacts the livestock growth rate and the biomass production at the village level.

6.4.3 Use of the CaTMAS model

CaTMAS can be used to simulate the C dynamics at a large scale such as region, country, etc. For example, at the country scale, a country can be viewed as a village territory composed of regions which can be viewed as farms. But, in the current version of the model, the climate is the same for the whole system. In addition, the farmers are situated randomly in the space. In order to provide a realistic application of the CaTMAS model at a large scale, the model would be improved to take into account the variation of the climate and the farmers' location as in the reality.

6.4.4 Coupling

The coupling CaTMAS with Century model allowed to provide a realistic representation of the C dynamics at different scales of time and space. This coupling provides a relevant framework to account social and bio-physical factors in C dynamics. The coupling of CaTMAS with Century is a loosely-coupling . Antle et al. (2001) determined three categories of model coupling defining the levels of the models integration: "loosely-coupled", "closely-coupled", and "fully integrated" . The "loosely-coupled" is based on the exchange of variables between sub-models. In the "closely-coupled" scheme, states or processes from one-model are linked directly to processes in another sub-model. In the "fully integrated" models, the sub-models have a same single set of drivers and endogenous variables.

Several authors discussed the issues of the models coupling (Matthews et al., 2005, Antle et al., 2001). These issues concern essentially the data conformity and the evolution of the models. For example, in "loosely-coupled", "closely-coupled" models, each model is independent and they do not behave necessarily at the same scales of time and space. It is necessary to ensure the conformity of data exchanged between sub-models for the coherency of the whole system. In the "closely-coupled" models, the modification of one sub-model could lead to the reorganisation of other sub-models. Antle et al. (2001) suggest the use of "fully integrated" scheme to ensure the coherency of the model.

In CaTMAS, the MAS part and the Century do not behave at the same time of scale. The MAS behaves at daily or monthly step while Century is executed at the yearly step. Century takes into account all events occurred during the year to simulate the C dynamics of the plots. This coupling does not allow to simulate the immediate effect of a perturbation on the C dynamics. For example, it is impossible to simulate the immediate impact of the animals grazing on plant growth. The behaviour of the model could be different if Century is executed at daily or monthly step. But the daily or monthly execution of the Century with CaTMAS is time and computer resources consuming and requires high-performance computers.

Century 5 and CaTMAS have been implemented with Object Oriented Programming (OOP) languages (C++ and Java). The OOP languages allow modular programming which makes easer the understanding, modifications and linking of software.

6.5 Conclusion

This chapter presented the CaTMAS model for the simulation of the C dynamics from plot to village levels while integrating the social and bio-physical factors. In CaTMAS, the heterogeneity of the system from social and bio-physical points of view are explicitly defined. Then, using the model, it is possible to compare the impacts of cropping systems on the C dynamics, to analyse the impact of the environment heterogeneity of the C dynamics on the individuals decision making. The coupling of the model with Century and GIS provides a realistic representation of the carbon dynamics.

In future, the model would be extended to simulate the C dynamics at a large scale, to take into account the adaptive behaviour of the farmers and make the CaTMAS a tool of dialog and communication between scientists, politics and the farmers.

Chapter 7

Conclusion

This study aimed at dealing with complex system (CS) representation and simulation. The question has two issues. Firstly, we are interested in the proposition of a framework which allows a multi-point of view description of a CS while integrating the macro-level, the micro-level and the underlying environment. Secondly, we are interested in the C dynamics modelling from plot to territory levels. The second part of our study is an application of the first part.

The chapter 2 allowed to define the properties of the CS and how dealing with their complexity. We showed that dealing with complexity require to take into account (1) a multi-point of view description and (2) the articulations between the macro and micro levels while integrating the underlying environment. The question is how to deal with multi-point of view description both at the macro and micro levels?, how to deal with the articulations between the macro and micro levels? Three theories in sociology discussed with the macro and micro levels articulations in sociology: the methodological holism, the methodological individualists and the methodological constructivism theories. The methodological holism asserts that the the macro level description does not take into account the nature of individuals. This theory is more interested in the macro phenomena than the micro phenomena. In contrast, the methodological individualists account only the micro-level and assumes the macro-level emerges from the individuals behaviour. Unlike, the methodological holism and methodological individualists theories, the methodological constructivism theory account both the macro and micro levels. The representation of a CS according to methodological constructivism theory requires to takes into account an explicit representation of the macro and micro levels. MASs are relevant in CS modelling when their representation requires to take into account both the micro-level, the micro-level and the underlying environment. Two approaches are currently used to describe the MASs structure: ACMAS and the OCMAS models. The ACMAS is based on the decomposition of a system in autonomous agents and assume that the global behaviour emerges from the agents interactions. OCMAS models assume that the social structure must exist *a priori* and constrains the agents behaviour. OCMAS models provide a framework to represent a system at the macro and micro levels and their articulation.

The chapter 3 presented a state of the art of the OCMAS. If most OCMAS models allow to take into account an explicit description of the macro and micro levels, they fail to provide an explicit separation between the macro and the micro levels. Another limitation of most OCMAS models concerns the environment representation. Most models have intended to take into account the environment in the organisation description but they fail to represent the agents' perception on their environment according to the roles they play in the system.

The chapter 4 presented the first contribution of our study: the OREA meta-model, a framework for multi-point of view description of the CS. The OREA meta-model is based on an extension of the AGR with includes the notion of aspects. The OREA model presents many advantages:

Separation between macro and micro level: The OREA meta-model allows a clear separation between the macro-level and the micro-level. The macro-level is defined without any assumption on the micro-level. Our objective is to define explicitly and separately the concerns in CS modelling: "what" and the "how". The macro-level describes the organisational structure i.e. the "what" while the micro-level describes the entities levels i.e. the "how". The relationships between these two levels of description are defined through the relations between roles and aspects. By separating the macro-level from the micro-level, the OREA model increases the reuse and evolution of an organisation structure. The modeller can describe the macro-level without knowing *a priori* what he/she will put at the micro-level. Then, with the same organisational structure, it is possible to define many configurations at the micro-level. Using the notion of role and aspect, OREA allows to separate the organisation behaviour from the entities local behaviour (from the internal point of view). The roles define the status of the entities and allow them to interact with each other. The aspects describe the entities internal features and specify how they behave and play roles. This specification allows managing the coherency from the local and global point of view. The macro-level controls the interactions between entities and, the entities control internally their own state through aspects.

polysemy of roles: In OREA, an entity can play simultaneously the same role type in different organisations and in different ways thanks to aspects.

the environment: The environment and its objects are defined explicitly in the organisation structure. They can play roles and interact with other entities. This specification allows defining the perception of the entities on their environment through their roles. Consequently, the OREA model supports simultaneously several environments in the same model.

In addition to a meta-model proposition, we have proposed a methodology. This methodology allows to describe the CS at different scales of description and the identification of entities through scales and roles (cf. section 4.5). However, the OREA model can be extended in many ways:

the environment: the OREA application in C dynamics modelling has showed that it would be necessary to include a generic organisation describing the environment for the ecosystem simulation. This extension would allow defining how the entities reason and act on their environment in a flexible way.

the hierarchical representation: the OREA would be extended in order to take into account the hierarchical description. The hierarchical description allows representing large scale systems and provides a flexible way to integrate coherently different models in a same model.

the role dependencies and incompatibilities: the roles can depend on each other. Then, when an entity requires a role, it has to play before all roles on which depends this role. In addition, some roles can be incompatible. As future works, the OREA model would be extended to express the dependencies relationships and to provide mechanism verifying the incompatibilities between the roles. That would allow ensuring the coherency of the system.

the graphical representation: in order to make easer the OREA use, a graphical user interface would be defined. Then, the designer can easily describe a conceptual model with OREA and implement the associated dynamics using the Mimosa features. Mimosa provides graphical formalism for the description of conceptual model. Then, the extension would consist in the adaptation of the Mimosa platform to OREA model.

The OREA meta-model has been applicated in C dynamics modelling. Using the OREA model, we had proposed the CaTMAS model presented in the chapter 5 and chapter 6. The CaTMAS model is an integrated model allowing to assess the C flows at village level while taking account the social, economic, physical and biological factors. The CatMAS model would be extended in many ways:

the C dynamics modelling at the regional or national scale the CaTMAS is applicable at the village level. The model would be extended in order to deal with C dynamics modelling at regional or national scale. The conceptual model of the OREA model makes possible this extension. At the regional or national level, it would be possible to analyse the C flows between villages, to take into account the domestics and the industries compartments. In addition, it would be possible to analyse the impact of climate change and the national policies on the C dynamics and poverty at the villages scale and vice-versa.

the economic potential of the C sequestration: the CaTMAS model does not take into account the economic returns of the C sequestration. The CaTMAS would be extended in order to assess the economic feasibility of agricultural soil carbon sequestration. Diagana et al. (2007) have used a spatially explicit econometric-process simulation model in order to simulate the impact of the carbon-payment schema on the C sequestration in Senegal. Their study has showed the importance of the econometric model in the C management. But their model does not take into account the social dimension e.g. the impact of the population change, the interactions between farmers, etc. A coupling of CaTMAS with an econometric model would allow a better analyse of the C dynamics.

Software extensions: concerns the implementation of the user interface to make easier the model use. In addition, the model would be coupled with a model which allows an explicit and generic representation of the spatial dynamics.

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Appendix A

The CatMAS data base description

Name	Description	type	unity	Valid values
site	Identity of the studied site	S		
description	Description of the site	S		
populationGrowthRate	The demography growth rate	F		
surface	The size of the site	I		
climate	The type of climate	S		
country	The the country location	S		

Table A.1: The Site table description

Name	Description	Type	Unity	Valid values
householdtype	The type of the household (a typology)	S		
numberOfhh	The number of households in this typology	I		
manpower	The initial number of persons	I		
farmsize	The initial size of the farm	I		
livestock	The initial size of the livestock	I		
extraIncome	Extra production source revenue	F		
immigration	Arrival of households	I		
immigrationfrequency	Frequency arrival (number of year)	I		
maxSize	The max size (number of persons) of a household	I		

Table A.2: The household table description

Name	Description	type	Unity	Valid values
Householdtype	The type of the household	S		
ageGroupStart	The beginning age of the group	I		
ageGroupEnd	The end age of the group	I		
Proportion	Proportion in the household	F		
deathRate	The death of the individual in the age group	F		
labor	Production labour provided	F		
energyNeed	The energy need	F		
moneyNeed	The money need	F		
migrationRate	The migration of the age group	F		

Table A.3: The householdStructure table description

Name	Description	type	Unity	Valid values
householdType	Household typology	S		
crop	The crop name	S		
selling	The crop sharing in the revenue source	N		
feeding	The crop sharing in the food requirement	N		

Table A.4: The foodsharing table description

Name	Description	type	Unity	Valid values
cropSystemID	The name of the cropping system	S		
description	The description	S		
fallowDuration	The fallow duration associated the cropping system	I		

Table A.5: The CroppingSystem table description

Name	Description	type	Unity	Valid values
rotationid	The identity of the record	I		
croppingSystem	The associated cropping system	S		
principalCrop	The principal crop in the rotation	S		
secondaryCrop	The secondary crop	S		
succession	The succession in the rotation	I		
treeRemoval	The type of tree removal in the succession	S		

Table A.6: The CropRotation table description

Name	Description	type	Unity	Valid values
crop	The type of the crop	S		
description	The description of the crop type	S		
energeticValue	The energetic value of the crop	N	Kcal/100g	
sellingPrice	The selling price	N	million	
purchasePrice	The purchase price	N	million	
grainN	N content of grain	N	g/100 g	
manualLabour	The labour required by the crop	N	days	
yield	The yield	N	t/yield	

Table A.7: The Crop table description

Name	Description	type	Unity	Valid values
operation	The type of task	S		
Crop	The crop name	S		
scheduledMonth	The month of task achieving	I		
repetition	The number of times the task is executed in the scheduled month	I		
typeOfOperation	The cultivation event	S		
additionalValue				

Table A.8: The FarmingCalendar table description

Name	Description	type	Unity	Valid values
typeOfMotorization				
price	The purchase price	N		
labour	The annual labour supplied	N		
wearing	The annual wearing			

Name	Description	type	Unity	Valid values
householdType	The type of household	S		
typeofmotorization	The type of motorization used by the household type	S		
levelOfMotorization	The level of motorization	N		

Name	Description	type	Unity	Valid values
contractType	The type of work contract	S		
description	The description of the work contract	S		
monthlySalary	The month salary	N	million	
duration	The contract duration	I	month	
cultivationLabour	Uses for the cultivation?	B		

Table A.11: The WorkContract table

Name	Description	type	Unity	Valid values
contractType	The type of contract	S		
householdType	The type of household	S		
employeeds	The number of employees	I		
proportion	The proportion of the household type using this contract	N		

Table A.12: The Employment table

Name	Description	type	Unity	Valid values
animalType	The name of the animal	S		

sellPrice	The selling price	N	Million/kg	
purchasePrice	The purchase price	N	Million/kg	
energyContent	The energy content	N	MJ/kg	

Table A.13: The Herd table

Name	Description	type	Unity	Valid values
animal	Type of the animal	S		
agegroupStart	The beginning of the age group	I	year	
ageGrouEnd	The end of the age group	I	year	
proportion	The proportion in the herd	N		
birthRate	The fecundity rate	N		
deathRate	The death rate	N		
selling	The selling rate	N		

Table A.14: The LiveStockStructure table

Name	Description	type	Unity	Valid values
livestock				
month	The month of the pasture	I		
pastureDuration	The number of hours in pasture	I	hour	
grazingLength	The daily length of the pasture	I	km/day	
biomassNeed	The daily biomass need	N	kg DM/kg/day	
faecesHourlyExcretion	The hourly faeces excretion	N	Kg DM/kg/day	
urineHourlyExcretion	The hourly urine excretion	N	litre/kg/day	
walkingSpeed	The walking speed	N	Km/hour	
grazingSpeed	The grazing speed		Kg DM/kg/hour	

Table A.15: The Pasture table

Name	Description	Type	Unity
gid	T		
LabelX			
LabelY			

LblOffsetX			
LblOffsetY			
Label			
Row			
Column			
RowCol			
the_geom			
occupation	The Crop/grass occupation	S	
typesoil	The type of soil	I	
grazing	The pasture path	B	
accessible	The plot accessibility	B	
owner	The owner	S	
unity	The geographical unity	I	
cropgrass			
forestcovert	The tree occupation	S	

Table A.16: The Plot Gis table

Name	Description	type	Unity
year	The year of the output	I	
month	The month of the output	I	
plot	The identifier of the plot	S	
aboveLiveC	The above live C	N	t/ha
aboveLiveN	The above live N	N	t/ha
bellowLiveC	The bellow live C	N	t/ha
bellowLiveN	The bellow live		t/ha
standingDeadC	The standing dead C	N	t/ha
standingDeadN	The standing dead N	N	t/ha
soilC	The soil C	N	t/ha
soilN	The soil N	N	t/ha
yield	The crop yield	N	t/ha
residueYield	The residue to remove	N	t/ha
occupation	The occupation of the plot	S	
culturalIntensity	The cultural intensity	N	
cropSystem	The cropping system applied on the crop	S	

Table A.17: The GlobalOutput table

Name	Description	type	Unity
year	The year of the output	I	
householdId	The household identity	S	
farmSize	The size of the household	I	
cash	The cash of the household	N	Million
food	The available cash	N	kCal
capitalProduction	The cash from crop production		

Table A.18: The HouseholdOutput table

Name	Description	type	Unity
year	The year of the output	I	
month	The month of the output	I	
day	The day of the output	I	
herdid	The identifier of the herd	S	
size	The size of the herd	I	
weight	The weight of the herd	N	kg
pastureLength	The pasture length	N	km
intake	The biomass intake	N	kg DM
excreted	The faeces excretion	N	Kg DM
urine	The urine excretion	N	litre

Table A.19: The HerdOutput table

Appendix B

CaTMAS results of simulation

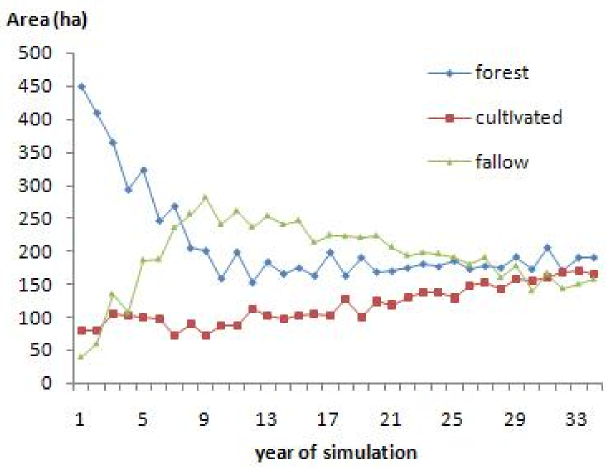

Figure B.1: Simulated evolution of land use extension in the C2 scenario

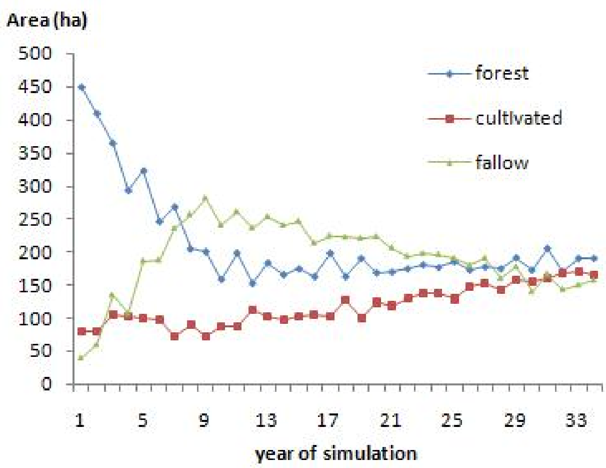

Figure B.2: Simulated evolution of land use extension in the C3 scenario

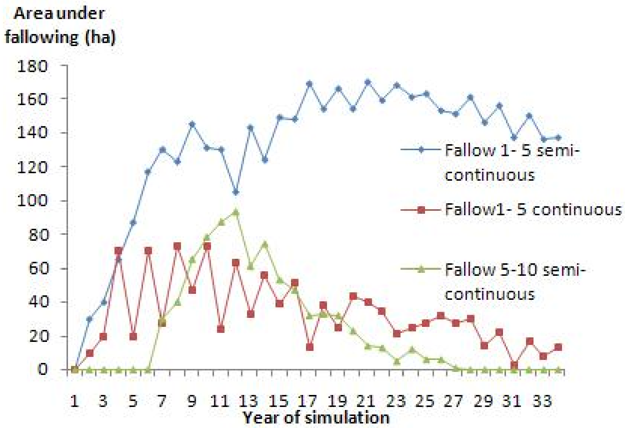

Figure B.3: Simulated evolution in SCS and CS of the extension of fallowing by class of fallow duration in C2

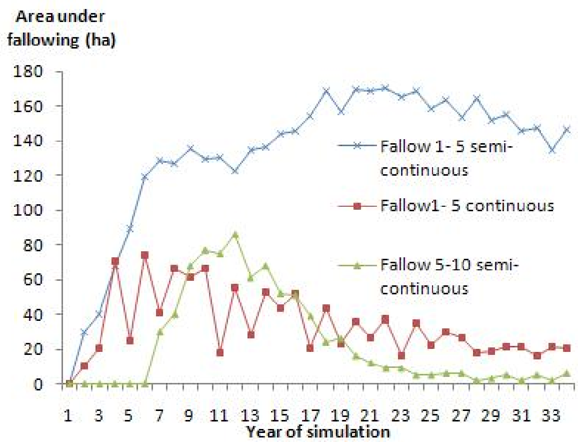

Figure B.4: Simulated evolution in SCS and CS of the extension of fallowing by class of fallow duration in C3 scenario

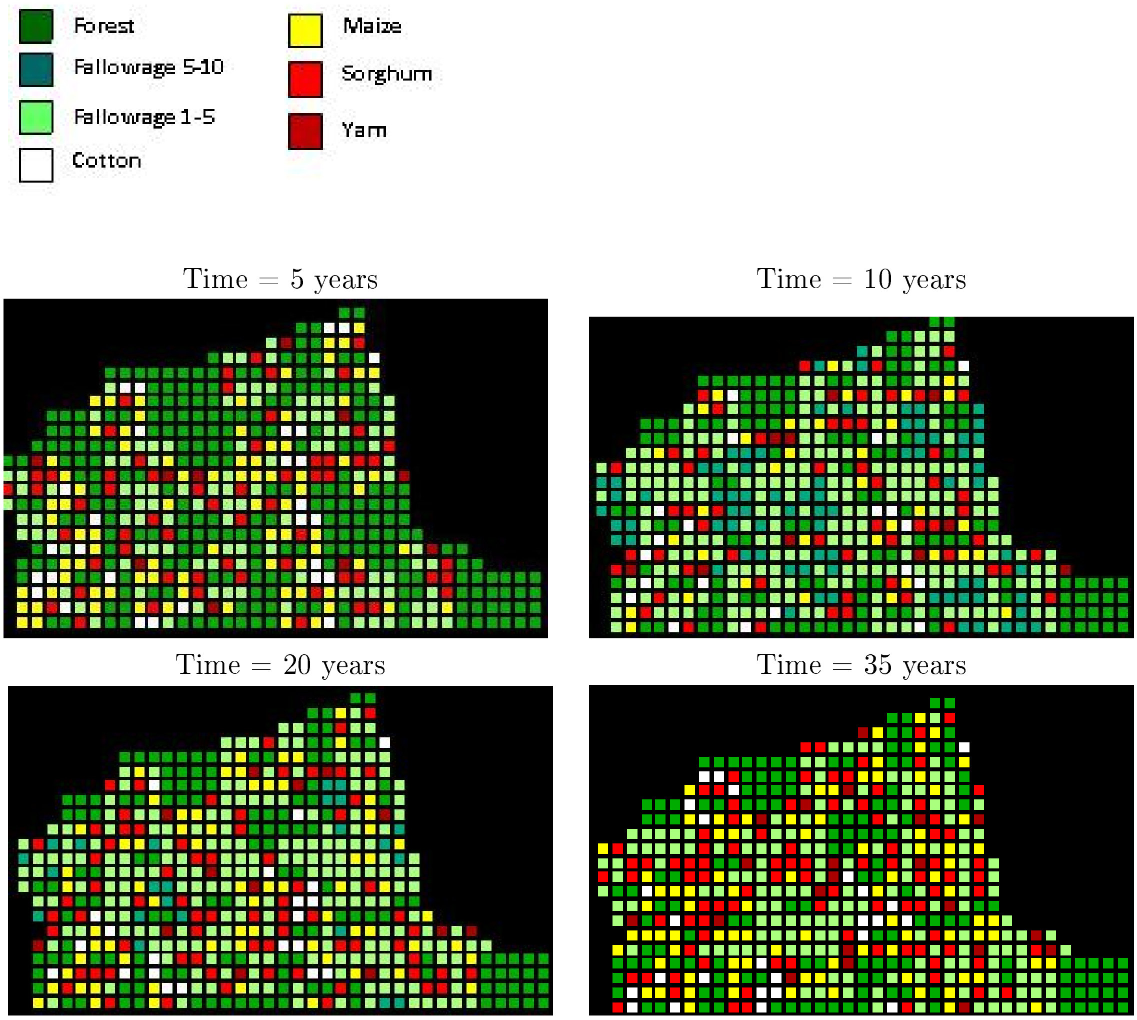

Figure B.5: Simulated evolution of the land use spatial distribution under the climate scenario C2

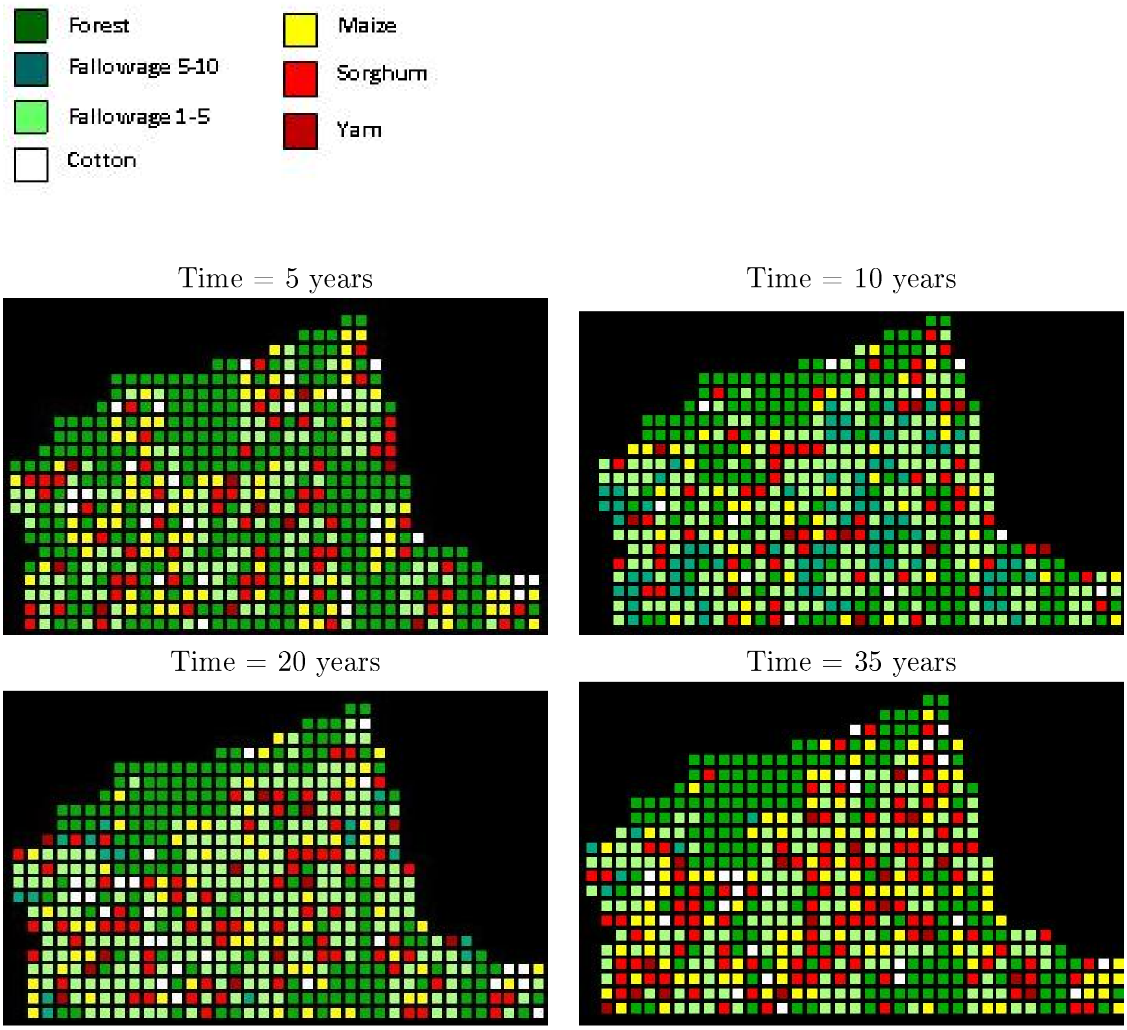

Figure B.6: Simulated evolution of land use spatial distribution under the climate scenario C3

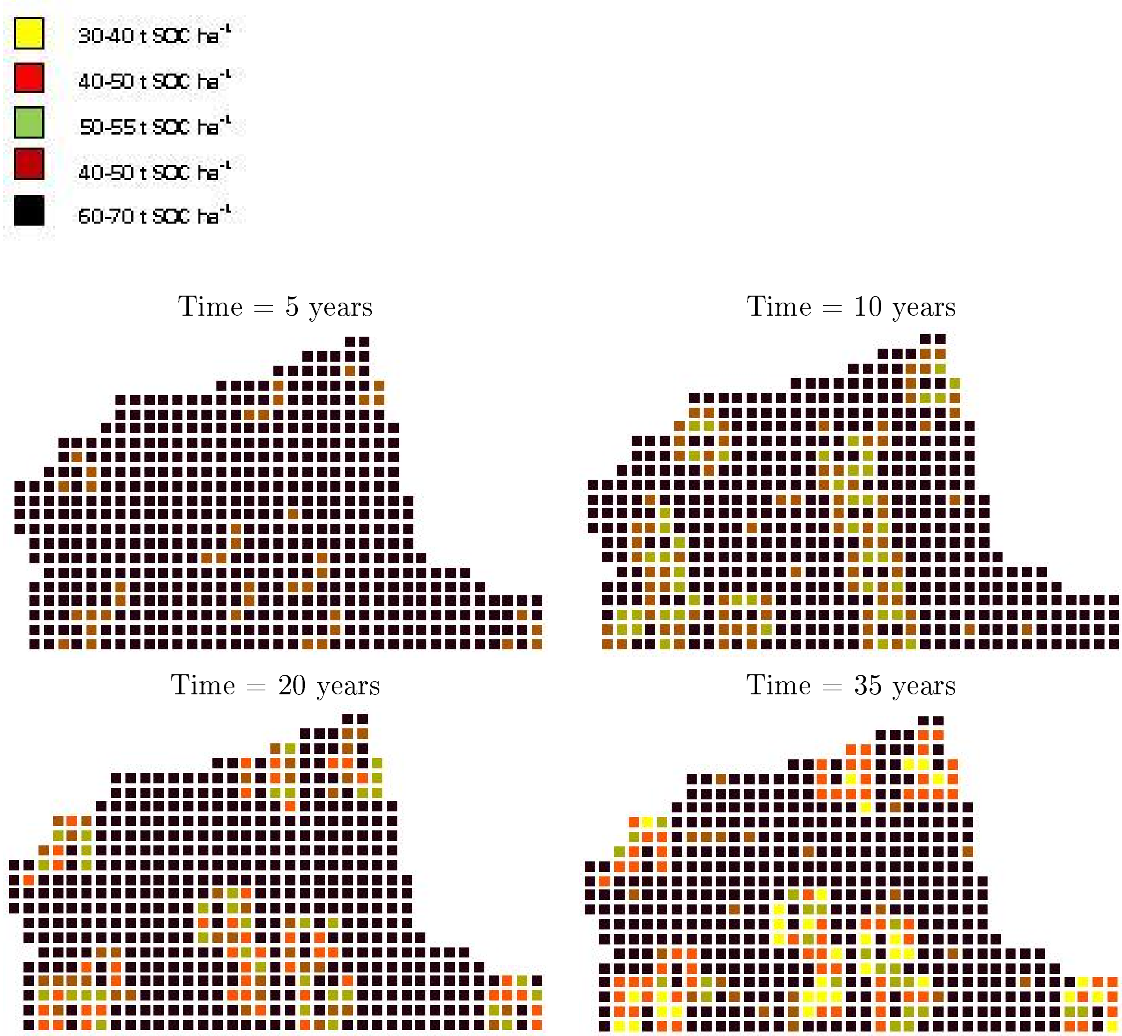

Figure B.7: Simulated evolution of SOC spatial distribution in scenario C1

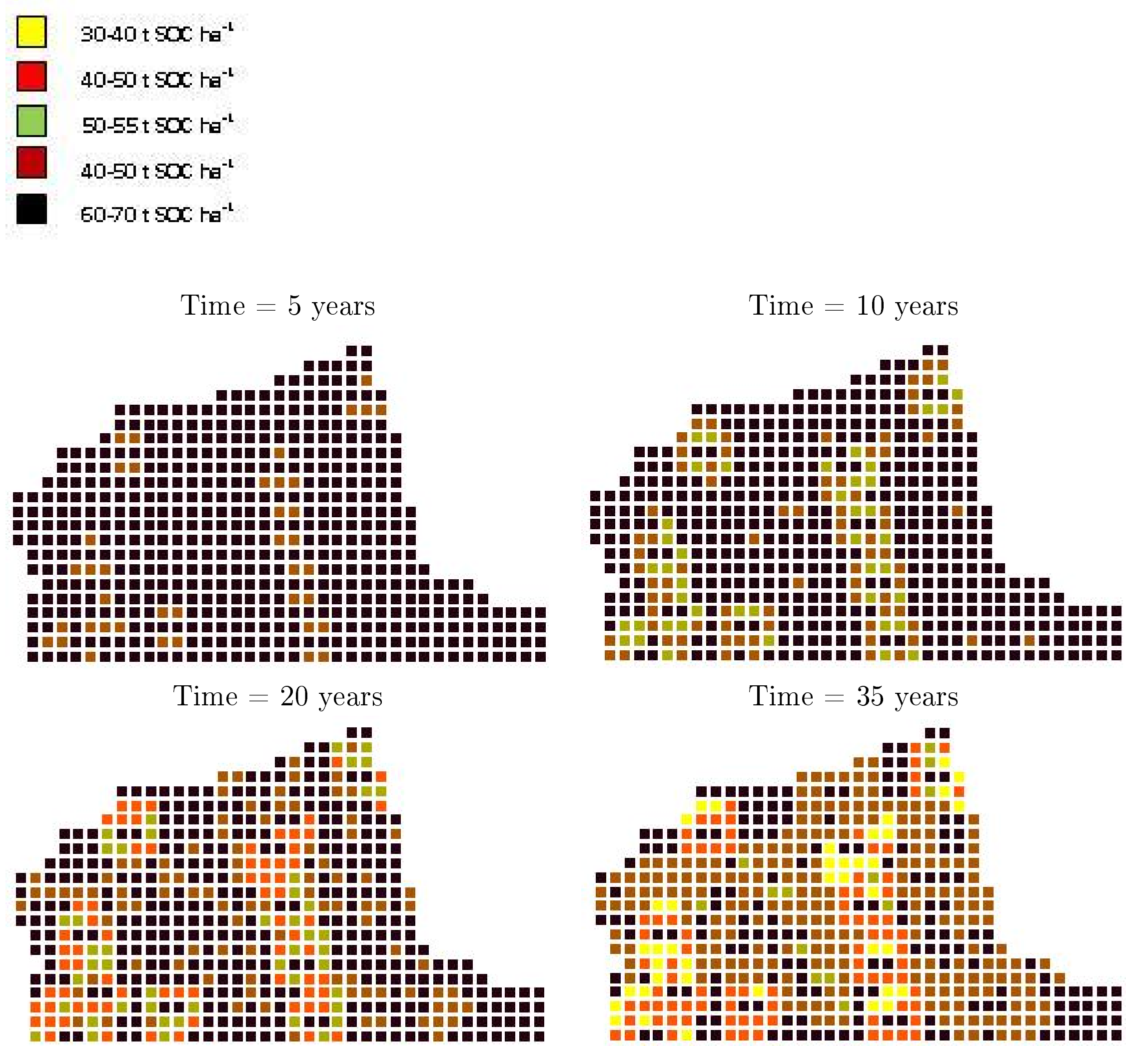

Figure B.8: Simulated evolution of SOC spatial distribution in scenario C2

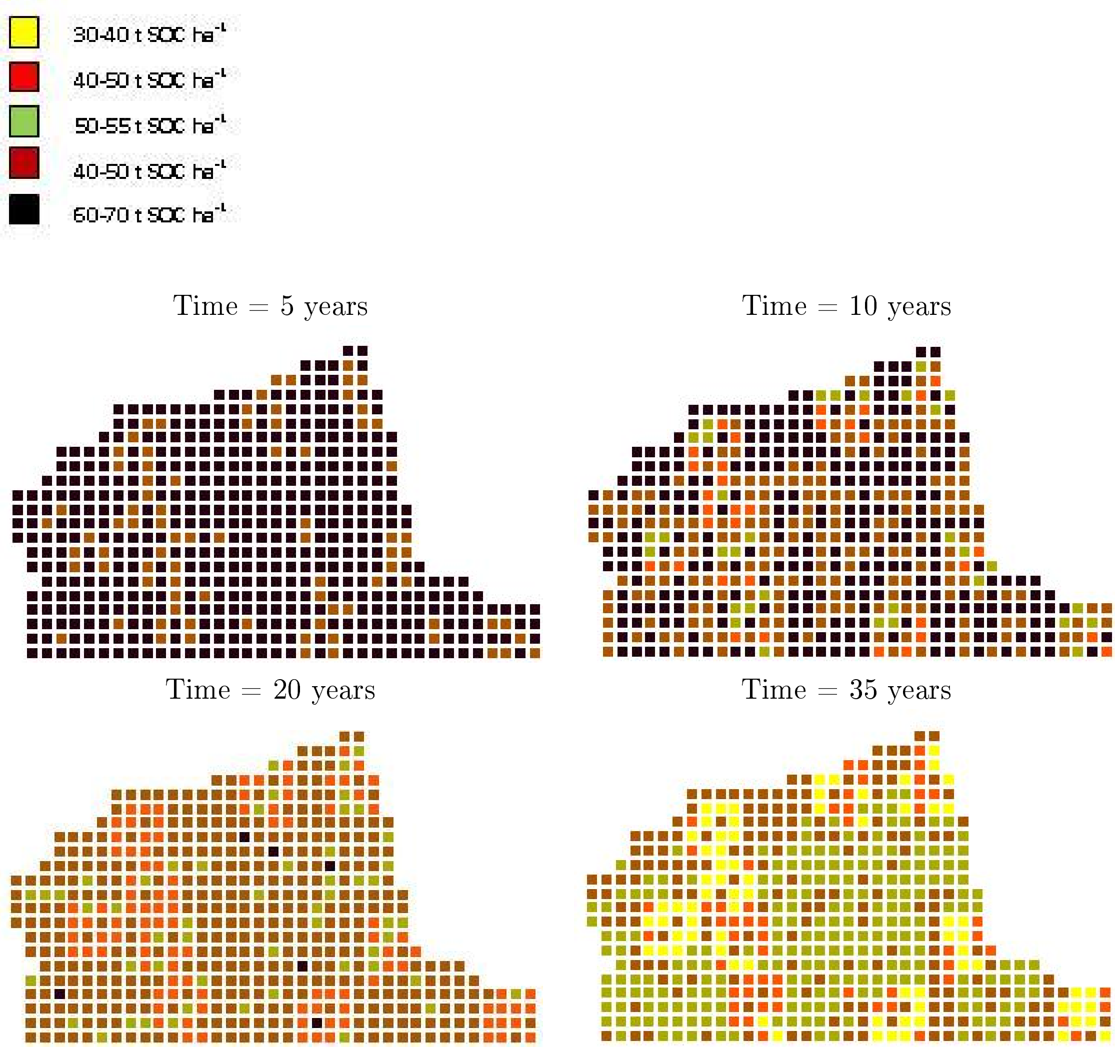

Figure B.9: Simulated evolution of SOC spatial distribution in scenario C3